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# 基于阿维菌素和呋虫胺增效组合的双载纳米微囊缓释剂对苹果黄蚜的防治效果

郭晓君[1]，封云涛[1]，李 娅[1]，王 琰[2]，张润祥[1*]

([1]山西农业大学植物保护学院·农业有害生物综合治理山西省重点实验室，太原 030031
[2]中国农业科学院农业环境与可持续发展研究所，北京 100081)

**摘 要：【目的】**研发苹果黄蚜可持续防控药剂及应用技术，为苹果黄蚜可持续防控提供优化方案。**【方法】**采用室内毒力及田间防效评价阿维菌素与呋虫胺对苹果黄蚜的联合毒力及二者纳米微囊缓释剂型的应用效果。**【结果】**室内毒力测定结果表明，阿维菌素与呋虫胺在1∶2和1∶4配比下对苹果黄蚜为增效作用；田间应用结果表明，阿维菌素和呋虫胺1∶4混配组合剂量(*w*)为15.0~22.5 $mg\cdot kg^{-1}$时对苹果黄蚜药后3~15 d防效为91.44%~99.63%，二者混配可减少单一药剂有效成分用量10%~70%。按该配比制备2.25%阿维·呋虫胺纳米微囊缓释剂，田间应用结果表明，在苹果黄蚜高发期施药两次，二次药后7~15 d对苹果黄蚜的防效为79.80%~91.65%，表现出较好的后期防效；添加助剂GY-T1602可有效改善纳米微囊缓释剂的速效性。**【结论】**在苹果黄蚜始发期，推荐使用2.25%阿维·呋虫胺纳米微囊缓释剂以获得较长持效期，添加助剂GY-T1602可有效提高防效；在苹果黄蚜盛发期推荐选用阿维菌素与呋虫胺1∶4混配组合以快速压低虫口密度。

**关键词：**苹果黄蚜；阿维菌素；呋虫胺；联合毒力；纳米微囊缓释剂

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## Synergistic effect of slow-releasing nanocapsules containing abamectin and dinotefuran on the control against *Aphis citricola*

GUO Xiaojun[1], FENG Yuntao[1], LI Ya[1], WANG Yan[2], ZHANG Runxiang[1*]

(*[1]College of Plant Protection, Shanxi Agricultural University (Institute of Plant Protection)/Shanxi Key Laboratory of Integrated Pest Management in Agriculture, Taiyuan 030031, Shanxi, China; [2]Institute of Environmental and Sustainable Development in Agriculture, Chinese Academy of Agricultural Science, Beijing 100081, China*)

**Abstract:**【Objective】In order to solve the problems of single type and reduced sensitivity of traditional insecticides for the control of *Aphis citricola* von der Goot on apple trees, the co-toxicity of abamectin and dinotefuran against *A. citricola* was examined, and the field experiment was carried out to verify the synergistic efficacy. Then, the application effect of the slow-releasing nanoparticles loading with the above two chemical pesticides was evaluated by field experiments for ultimately obtaining the control plan for *A. citricola*.【Methods】Indoor bioassay was carried out by leaf dipping method. Experimental insects were gathered from apple trees in the greenhouse of Dongyang Experimental Base, Shanxi Agricultural University, which were not treated with any pesticides. Four combinations of abamectin and dinotefuran were set up by the active ingredient ratios of 1∶2, 1∶4, 1∶8 and 1∶16. Firstly, fresh and tender leaves were immersed in the insecticide solutions for 5 seconds, and then moved back up into a petri dish covered with wet filter paper. Secondly, healthy adult aphids were chosen and placed to the leaf surface for incubation, and the mortality was recorded after 24 hours of feeding. The co-toxicity of abamec-

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**作者简介：**郭晓君，女，副研究员，研究方向为农业害虫防治及农药综合利用。E-mail：guoxj0302@126.com

*通信作者 Author for correspondence. E-mail：973588211@qq.com

tin and dinotefuran to *A. citricola* was evaluated by Sun Yunpei's co-toxicity coefficient method. Based on the co-toxicity results, two field trials were conducted to evaluate the control effects in April and June, 2021, in Yuncheng City, Shanxi province. Five treatments were set up in each experiment. There were three different doses of the compound (abamectin 5% EC and dinotefuran 20% SG) and two single insecticide (abamectin 5% EC or dinotefuran 20% SG). The three doses were 4, 9 and 13.5 mg·kg$^{-1}$ at 1∶2 ratio, respectively; as well as 15, 20 and 22.5 mg·kg$^{-1}$ at 1∶4 ratio, respectively. Water was set up as the control. Knapsack sprayer was used to evenly spray the apple tree with the amount of 2–3 L solution per tree. Each treatment had 4 replications, and there were 2 trees in each replication. The insect population number was investigated on the 3rd, 7th and 15th day after application. In addition, 2.25% abamectin ·dinotefuran co-delivery nanoparticles formulation (2.25% DACNPs) at the ratio of 1∶4 was prepared and applied. The field experiment was carried out from May to June, 2022 in Linyi county, Shanxi province. Four treatments were designed for the experiment, including 2.25% DACNPs, the compound at 1∶4 ratio, and the addition of the additive GY-T1602 to both, respectively. It was applied twice during the occurrence period of aphids and the insect population was investigated on 7th and 15th day after each application. Finally, the population decline rates and the control effects were calculated. 【Results】When the compound ratio of abamectin and dinotefuran were at 1∶2, 1∶4 and 1∶8, the co-toxicity coefficients (CTC) on *A. citricola* were 251.61, 260.72 and 126.25, respectively. They were greater than 120, indicating that these ratios had synergistic effect on *A. citricola*. The $LC_{50}$ of abamectin was 0.66 mg·L$^{-1}$, while the dinotefuran was 106.44 mg·L$^{-1}$. The $LC_{50}$ of the combinations at the ratio of 1∶2 and 1∶4 were 0.75 and 1.28 mg·L$^{-1}$, respectively. It showed that the combinations could enhance the toxicity of dinotefuran significantly. Field trials showed that, at the ratio of 1∶2, when the dosages were 4.5 and 9 mg·kg$^{-1}$, the control effects against *A. citricola* in 7–15 days were only 51.69%–78.46%, significantly lower than those of any single agent. At the dosage of 13.5 mg·kg$^{-1}$, the control effect was comparable to dinotefuran alone, but still lower than that of abamectin, and the difference among all of them was not significant. At the ratio of 1∶4, the control effects in 3 days were 91.44%–99.63% at the dosages of 15, 20 and 22.5 mg·kg$^{-1}$, which were equivalent to or slightly higher than abamectin or dinotefuran alone. However, the combination could reduce the active constituent amount of abamectin or dinotefuran by the range of 10%–70%. Moreover, the control effect of 2.25% DACNPs against *A. citricola* in 7–15 days after the first application was 41.44%–64.58%, which was lower than that of the 1∶4 combination. After the secondary application, the control effect of 2.25% DACNPs in 7–15 days was 79.80%–91.65%, which was equivalent to the 1∶4 combination. The results also indicated that the 2.25% DACNPs had sustainable efficacy on the control against *A. citricola*. By adding adjuvant GY-T1602, compared with the same treatment without the addition, the control effects were all improved to a certain degree, there were significant difference in the 7 days after the first application, but no significant difference existed in the other days. It indicated that adding adjuvant could improve the quick effect. 【Conclusion】It is recommended to use 2.25% DACNPs in initial occurrence of *A. citricola*. However, the combination of abamectin and dinotefuran at the ratio of 1∶4 should be used in peak occurrence to reduce the insect population density quickly. Adding adjuvant GY-T1602 in the spray could obtain a higher efficacy, especially in the early control effect.

**Key words:** *Aphis citricola*; Abamectin; Dinotefuran; Co-toxicity; Co-delivery nanoparticles formulation

苹果黄蚜(*Aphis citricola* von der Goot)，又称绣线菊蚜，群聚危害苹果树嫩叶和新梢，造成叶片向内或向下卷曲，分泌的蜜露覆盖在叶片表面，甚至可作为病菌传播媒介致“煤污病”，严重影响果树的光合作用[1-2]。在苹果黄蚜的化学防治中，有机磷类、菊酯类和新烟碱类等杀虫剂的长期过量使用已造成害虫敏感性下降，导致防治效果不佳[3-4]。寻找新的替代或轮换药剂，是当前苹果园化学防治中急需解决的关键问题之一。呋虫胺(dinotefuran)最早由日本三井化学合成并登记，为一种乙酰胆碱受体激动剂，因与新烟碱类杀虫剂结构不同，也称为第三代烟碱类杀虫剂，自2014年在中国正式登记以来，已报道用于多种刺吸式口器害虫的防治[5-6]。阿维菌素(abamectin)属于大环内酯类杀虫杀螨剂，具有杀虫谱广、杀虫活性高的特点，尽管因长期过量使用阿维菌素，已有多种害虫对其产生了抗药性[7]，但笔者课题组前期研究表明，阿维菌素对苹果黄蚜的活性较其他几种杀虫剂高[8]，在防治苹果黄蚜中依然具有较高的应用价值。杀虫剂复配，尤其是将两种及以上不同作用机制的杀虫剂复配，可实现作用机制互补、扩大杀虫谱、提高农药活性、减少农药使用量，同时降低交互抗性风险，延缓害虫抗性发展，实现农药可持续利用[9]。目前，针对阿维菌素或呋虫胺与其他药剂复配的应用案例均有报道[2,10-11]，而关于这两者复配的研究极少。笔者课题组前期报道了阿维菌素和呋虫胺混配对梨园梨木虱有延长持效期、提高防效的作用[12]，对苹果园主要害虫苹果黄蚜的应用效果尚不明确。因此，笔者在本研究中通过明确阿维菌素和呋虫胺对苹果黄蚜的联合毒力，开展基于二者增效配比的纳米微囊缓释剂型对苹果黄蚜的田间应用技术研究，以期为苹果黄蚜可持续防控提供优化方案。

## 1 材料和方法

### 1.1 供试生物试材

室内毒力测定于2021年4月进行。室内毒力测定所用苹果黄蚜成蚜采自山西省农业科学院东阳基地温室苹果树，现采现用。试验年份未施用任何农药。

### 1.2 供试药剂

96%阿维菌素原粉(TC，河北威远生物化工有限公司生产)；91.2%呋虫胺原粉(TC，江苏克胜作物科技有限公司生产)；5%阿维菌素乳油(EC，天津市汉邦植物保护剂有限责任公司生产)；20%呋虫胺可溶粒剂(SG，日本三井化学AGRO株式会社生产)；2.25%阿维菌素•呋虫胺纳米微囊缓释剂[13](中国农业科学院农业环境与可持续发展研究所制备)。

### 1.3 试验方法

1.3.1 药剂毒力测定 于正式试验前进行预试验确定药剂配比及浓度。设置阿维菌素与呋虫胺有效成分比1∶2、1∶4、1∶8和1∶16共4个复配组合。药液配制时，按有效成分比例分别量取阿维菌素和呋虫胺原粉，用丙酮溶解并配制成一定浓度的母液，再用蒸馏水稀释成5~7个浓度梯度。

采用浸渍法测定药剂对苹果黄蚜的毒力。将新鲜苹果幼嫩叶片浸入药液中5 s后取出，用吸水纸吸取多余药液，将叶片背面向上置于铺有湿滤纸的培养皿中，用毛笔挑选大小一致的健康无翅成蚜放于叶片上，置于人工培养箱中饲养24 h [温度(25±1) ℃，湿度65%±5%，光照L16∶D8]，检查死亡率。每个处理4次重复，每个重复不少于25头成蚜，以蚜虫不能自主爬行为死亡判断标准，记录总虫数和死虫数。

1.3.2 混配组合田间防效验证 根据联合毒力评价结果，选择阿维菌素与呋虫胺1∶2和1∶4组合开展田间验证。采用5%阿维菌素乳油与20%呋虫胺可溶粒剂配制混配组合，每种配比分别设3个剂量处理，其中1∶2混配组合为4.5(1.5∶3)mg·kg$^{-1}$、9(3∶6)mg·kg$^{-1}$和13.5(4.5∶9)mg·kg$^{-1}$，1∶4复配组合为15(3∶12)mg·kg$^{-1}$、20(4∶16)mg·kg$^{-1}$和22.5(4.5∶18)mg·kg$^{-1}$，同时设5%阿维菌素EC 5 mg·kg$^{-1}$、20%呋虫胺SG 40 mg·kg$^{-1}$单剂对照及清水对照。阿维菌素与呋虫胺1∶2混配组合田间试验于2021年4月29日在山西省运城市盐湖区杨包农场进行，苹果品种为美八，树龄14 a(年)；1∶4混配组合试验于同年6月8日在运城市临猗县角杯乡进行，苹果品种为富士，树龄6 a。施药时均采用新加坡利农PJ-16型背负式喷雾器，施药量为2~3 L•株$^{-1}$。每处理设4次重复，每重复固定2株树，在树冠东、西、南、北、中5个方位随机取8个枝条，选取各枝条顶梢5~8片叶挂牌，施药当天调查虫口基数，药后3、7、15 d调查残虫数。

1.3.3 2.25%阿维菌素•呋虫胺双载纳米微囊缓释剂应用研究 2.25%阿维菌素•呋虫胺双载纳米微

囊缓释剂试验于2022年5—6月在山西省运城市临猗县角杯乡进行，试验苹果品种富士，树龄5 a，施药时间分别为5月18日和6月3日，采用新加坡利农PJ-16型背负式喷雾器均匀喷施，施药量为2~3 L•株$^{-1}$。同时设置药剂及与助剂GY-T1602[8, 14]联合使用处理，试验设计见表1。每处理设4次重复，每重复固定2株树。试验及调查方法同1.3.2，施药当天调查虫口基数，分别于各次药后7 d和15 d调查残虫数。

### 1.4　数据分析与处理

1.4.1　联合毒力评价　根据Probit几率值法计算阿维菌素和呋虫胺单剂及复配药剂的毒力回归方程、致死中浓度$LC_{50}$、卡方及95%置信限。采用Sun等[15]方法计算复配药剂的共毒系数CTC，其中当CTC＜80表示为拮抗作用，80≤CTC＜120表示为相加作用，CTC≥120表示为增效作用。

1.4.2　田间防效分析　根据药前虫口基数和药后残虫数，分别计算各处理区和对照区的虫口减退率和防治效果。采用SPSS软件对各处理防效进行单因素方差分析，并利用Duncan's新复极差法进行差异显著性分析。

虫口减退率/%=

$$\frac{\text{药前虫口基数}-\text{药后存活虫口数}}{\text{药前虫口基数}}\times 100；$$

防治效果/%=

$$\frac{\text{处理组虫口减退率}-\text{对照组虫口减退率}}{100-\text{对照组虫口减退率}}\times 100。$$

**表1　2.25%阿维・呋虫胺双载纳米微囊缓释剂防治苹果黄蚜田间试验方案**

**Table 1　Field trial scheme of 2.25% abamectin·dinotefuran co-delivery nanoparticles formulation against *A. citricola***

| 处理<br>Treatment | 药剂<br>Pesticides | 有效成分用量<br>Dosage of active ingredients/(mg·kg$^{-1}$) |
|---|---|---|
| A | 2.25%阿维•呋虫胺双载纳米微囊缓释剂2.25% DACNPs | 15 |
| B | 5%阿维菌素乳油+20%呋虫胺可溶粒剂Abamectin 5% EC+ Dinotefuran 20% SG | 3+12 |
| C | 2.25%阿维•呋虫胺双载纳米微囊缓释剂+0.3% GY-T1602<br>2.25% DACNPs +0.3% GY-T1602 | 15 |
| D | 5%阿维菌素乳油+20%呋虫胺可溶粒剂+0.3% GY-T1602<br>Abamectin 5% EC+ Dinotefuran 20% SG +0.3% GY-T1602 | 3+12 |
| E | 清水对照 Water control | − |

注：表中"−"表示不适用此项。下同。

Note: The "−" in the table indicates that the item is not available. The same below.

## 2　结果与分析

### 2.1　阿维菌素和呋虫胺对苹果黄蚜的联合毒力

室内毒力测定结果见表2，阿维菌素对苹果黄蚜的毒力较高，致死中质量浓度$LC_{50}$为0.66 mg·L$^{-1}$，呋虫胺对苹果黄蚜的致死中质量浓度$LC_{50}$为106.44 mg·L$^{-1}$，毒力仅为阿维菌素的1/160。联合毒力测定结果表明，将阿维菌素与呋虫胺按一定比例复配，仅配比为1∶16时对苹果黄蚜显示为拮抗作用，配比为1∶2、1∶4和1∶8时共毒系数CTC为126.25~260.72、均大于120，表明这三种配比下对苹果黄蚜有增效作用。其中配比为1∶2和1∶4时$LC_{50}$分别为0.75 mg·L$^{-1}$和1.28 mg·L$^{-1}$，相比呋虫胺单剂毒力大大提高，增效作用显著。

**表2　阿维菌素和呋虫胺对苹果黄蚜的联合毒力**

**Table 2　Co-toxicity of abamectin and dinotefuran against *A. citricola***

| 药剂<br>Pesticides | 配比<br>Ratio | 毒力方程<br>Toxicity equation | 斜率±标准误<br>Slope±SE | 致死中质量浓度（95%置信限）<br>$LC_{50}$ (95% CI)/(mg·L$^{-1}$) | 卡方值（自由度）<br>Chi-square (df) | 共毒系数<br>Co-toxicity coefficient (CTC) |
|---|---|---|---|---|---|---|
| 阿维菌素+呋虫胺<br>Abamectin and dinotefuran | 1∶0 | $y$=2.17$x$+5.40 | 2.17±0.19 | 0.66(0.52~0.83) | 7.44(4) | − |
| | 0∶1 | $y$=1.71$x$+1.53 | 1.71±0.19 | 106.44(78.23~144.81) | 5.78(4) | − |
| | 1∶2 | $y$=1.12$x$+5.13 | 1.02±0.13 | 0.75(0.43~1.29) | 4.39(4) | 260.72 |
| | 1∶4 | $y$=0.91$x$+4.90 | 0.91±0.16 | 1.28(0.58~2.87) | 1.85(4) | 251.61 |
| | 1∶8 | $y$=1.03$x$+4.33 | 1.03±0.15 | 4.48(2.58~7.81) | 0.70(4) | 126.25 |
| | 1∶16 | $y$=1.89$x$+2.59 | 1.89±0.18 | 18.82(14.06~25.19) | 2.81(4) | 54.27 |

### 2.2 阿维菌素和呋虫胺混配对苹果黄蚜的田间应用效果

阿维菌素+呋虫胺1∶2混配组合对苹果黄蚜的田间防效见表3。结果表明，各处理对苹果黄蚜药后3 d防效均很低，可能与苹果黄蚜正处于繁殖高峰有关。药后7~15 d，5%阿维菌素EC单剂对苹果黄蚜的防效最高，均在90%以上；20%呋虫胺SG单剂对苹果黄蚜的防效低于阿维菌素，但无显著差异；1∶2混配组合施用剂量为4.5和9.0 mg·kg$^{-1}$时，对苹果黄蚜防效仅为51.69%~78.46%，均低于单剂对照；施用剂量为13.5 mg·kg$^{-1}$时药后各天防效可与呋虫胺单剂持平，但仍低于阿维菌素单剂，差异未达显著水平。

阿维菌素+呋虫胺1∶4混配组合对苹果黄蚜的田间防效见表4。各处理中，5%阿维菌素EC 5 mg·kg$^{-1}$处理药后3~15 d对苹果黄蚜的防效为95.64%~99.47%，20%呋虫胺SG 40 mg·kg$^{-1}$处理药后3~15 d防效为81.74%~97.48%；阿维菌素+呋虫胺1∶4混配处理在剂量为15.0、20.0及22.5 mg·kg$^{-1}$下，药后3~15 d对苹果黄蚜的防效在91.44%~99.63%之间，药后各天防效均高于呋虫胺单剂，与阿维菌素相当。

表3 阿维菌素和呋虫胺1∶2复配对苹果黄蚜的田间防治效果

Table 3 Field efficacy of abamectin and dinotefuran in 1∶2 ratio against *A. citricola*

| 药剂 Pesticides | 有效成分用量 Dosages of active ingredients/(mg·kg$^{-1}$) | 防效 Efficacy/% | | |
|---|---|---|---|---|
| | | 药后3 d 3 days after treatment | 药后7 d 7 days after treatment | 药后15 d 15 days after treatment |
| 5%阿维菌素EC Abamectin 5% EC | 5.0 | 58.82±9.89 a | 90.01±0.72 a | 94.82±2.02 a |
| 20%呋虫胺SG Dinotefuran 20% SG | 40.0 | 46.09±9.99 a | 78.95±5.45 ab | 85.67±2.55 ab |
| 5%阿维菌素EC +20%呋虫胺SG Abamectin 5% EC+ Dinotefuran 20% SG | 4.5(1.5+3) | 15.43±4.84 b | 51.69±6.63 c | 71.51±11.45 b |
| | 9.0(3+6) | 17.80±4.28 b | 69.98±3.78 b | 78.46±6.14 ab |
| | 13.5(4.5+9) | 49.74±11.15 a | 81.80±4.15 ab | 85.48±3.01 ab |

注：括号内数字分别为阿维菌素和呋虫胺有效成分用量。表中防效为"平均值±标准误"，同列不同英文字母"a, b, c"表示采用邓肯氏检验在$p<0.05$水平差异显著。下同。

Note: The numbers in parentheses indicate the active ingredient dosages of abamectin and dinotefuran. The control efficacy in the table was the "mean ± standard error", the different English letters "a, b, c" in the same column indicate that there is a significant difference at the $p<0.05$ level using Duncan's test. The same below.

表4 阿维菌素和呋虫胺1∶4复配对苹果黄蚜的田间防治效果

Table 4 Field efficacy of abamectin and dinotefuran in 1∶4 ratio against *A. citricola*

| 药剂 Pesticides | 有效成分用量 Amount of active ingredients/(mg·kg$^{-1}$) | 防效 Efficacy/% | | |
|---|---|---|---|---|
| | | 药后3 d 3 days after treatment | 药后7 d 7 days after treatment | 药后15 d 15 days after treatment |
| 5%阿维菌素EC Abamectin 5% EC | 5.0 | 99.47±0.19 ab | 98.90±0.49 a | 95.64±2.37 a |
| 20%呋虫胺SG Dinotefuran 20% SG | 40.0 | 97.48±0.13 c | 94.43±0.73 b | 81.74±2.74 b |
| 5%阿维菌素EC +20%呋虫胺SG Abamectin 5% EC+ Dinotefuran 20% SG | 15.0(3+12) | 98.82±0.39 b | 98.70±0.68 a | 91.72±6.25 ab |
| | 20.0(4+16) | 99.63±0.15 a | 98.88±0.32 a | 91.44±4.10 ab |
| | 22.5(4.5+18) | 99.45±0.21 ab | 98.66±0.51 a | 94.04±3.26 ab |

在本研究试验条件下，供试药剂对苹果黄蚜的速效性和持效性均较好，各处理均在药后3 d防效达到最高，药后15 d除呋虫胺单剂对照防效较低为81.74%外，其余各处理防效仍在91%以上。且与单剂对照相比，可分别减少阿维菌素和呋虫胺有效成分用量10%~40%和55%~70%。

### 2.3 2.25%阿维菌素·呋虫胺双载纳米微囊缓释剂的应用

根据上述获得的增效配比1∶4，制备了2.25%阿维菌素·呋虫胺双载纳米微囊缓释剂，并与阿维菌素和呋虫胺1∶4混配组合进行了田间应用对比，结果见表5。一次药后7 d，2.25%阿维菌素·呋虫胺双载纳米微囊缓释剂对苹果黄蚜的防效为41.44%，显著低于混配组合；药后15 d微囊缓释剂处理防效上升至64.58%，仍低于1∶4混配组合，差异不显著。二次药后7 d，微囊缓释剂和混配组合处理对苹果黄蚜的防效分别为79.80%和82.73%；二次药后15 d微囊缓释剂防效略高于混配组合，防效分别为91.65%和

表5　2.25%阿维菌素·呋虫胺双载纳米微囊缓释剂对苹果黄蚜的田间防治效果

Table 5　Field efficacy of 2.25% DACNPs against *A. citricola*

| 处理 Treatment | 虫口基数 Insect population/heads | 一次药后7 d 7 days after the first treatment | | 一次药后15 d 15 days after the first treatment | | 二次药后7 d 7 days after the second treatment | | 二次药后15 d 15 days after the second treatment | |
|---|---|---|---|---|---|---|---|---|---|
| | | 虫口减退率 Decline rate/% | 防效 Efficacy/% | 虫口减退率 Decline rate/% | 防效 Efficacy/% | 虫口减退率 Decline rate/% | 防效 Efficacy/% | 虫口减退率 Decline rate/% | 防效 Efficacy/% |
| A | 3 195.25 | −30.89 | 41.44±6.03 c | −183.63 | 64.58±1.17 b | 75.25 | 79.80±3.51 b | 93.26 | 91.65±3.32 ab |
| B | 2 618.50 | 12.24 | 60.74±9.68 ab | −113.98 | 73.28±7.38 ab | 78.84 | 82.73±3.62 ab | 91.87 | 89.92±1.82 b |
| C | 1 750.00 | 4.63 | 57.33±1.23 b | −133.27 | 70.87±3.40 ab | 81.17 | 84.63±6.35 ab | 96.02 | 95.06±3.01 a |
| D | 2 439.25 | 34.15 | 70.54±7.90 a | −62.54 | 79.70±8.18 a | 84.15 | 87.06±2.49 a | 94.03 | 92.60±1.02 ab |
| E | 1 343.00 | −123.52 | – | −700.76 | – | −22.52 | – | 19.37 | – |

注：处理A、B、C、D、E及用量见表1。其中，A为2.25% DACNPs；B为阿维菌素与呋虫胺1∶4混配组合；C为2.25% DACNPs+助剂GY-T1602；D为阿维菌素与呋虫胺1∶4混配+助剂GY-T1602；E为清水对照。

Note: The pesticides and dosage of the A, B, C, D and E were showed in Table 1. Among them, A was 2.25% DACNPs; B was the 1∶4 combination of abamectin and dinotefuran; C was 2.25% DACNPs + adjuvant GY-T1602; D was the 1∶4 combination of abamectin and dinotefuran + adjuvant GY-T1602; E was water control.

89.92%，两处理间均无显著差异。表明阿维菌素和呋虫胺1∶4混配组合对苹果黄蚜速效性好，而2.25%阿维菌素•呋虫胺双载纳米微囊缓释剂对苹果黄蚜后期防效更好、持效期长，这与微囊缓释剂为控制释放、活性成分释放慢有关。

进一步研究了各处理添加助剂对苹果黄蚜的应用效果。结果表明，与未加助剂相比防效均有所提高，其中2.25%阿维菌素•呋虫胺双载纳米微囊缓释剂在一次药后7 d和15 d对苹果黄蚜的防效分别提高15.89和6.29个百分点，药后7 d达显著水平；二次药后7 d和15 d微囊缓释剂处理对苹果黄蚜的防效分别上升至84.63%和95.06%，均高于未添加助剂处理，但无显著差异。与混配组合相比，趋势与未添加助剂时相同，微囊缓释剂处理在一次药后7 d、15 d和二次药后7 d防效均低于混配组合，其中一次药后7 d差异显著；二次药后15 d微囊缓释剂处理防效高于混配组合，但无显著差异。该结果表明，添加助剂可在一定程度上提高防效，尤其可改善2.25%阿维•呋虫胺双载纳米微囊缓释剂对苹果黄蚜的前期防效。

## 3　讨　论

笔者在本研究中通过室内联合毒力和田间验证评价了阿维菌素和呋虫胺对苹果黄蚜的增效作用，获得了二者最佳增效配比1∶4，进一步评价了基于该配比的二者纳米缓释剂型的田间应用效果。研究发现，各次试验方案田间防效差异较大，原因可能是苹果黄蚜种群在各试验阶段处于不同的自然消长态势，且田间试验影响因素复杂，重现性差。特别是2.25%阿维•呋虫胺双载纳米微囊缓释剂，第一次施药后正值种群急剧增长期，药后15 d各处理虫口数均为正增长，随后进行了二次补充施药；末次调查后，由于果树新梢老化、苹果黄蚜种群迁移，对照组虫口数量急剧下降，导致防效无法计算，调查中止，其持效期还需进一步验证。

在生产中，将已有常规剂型进行混配是较为经济快捷的方式。在本研究中，阿维菌素和呋虫胺在配比1∶4、设计用量为15.0、20.0和22.5 mg · kg$^{-1}$时对苹果黄蚜均有较好的防效，与单剂相比，中等剂量20.0 mg · kg$^{-1}$（其中阿维菌素4 mg · kg$^{-1}$、呋虫胺16 mg · kg$^{-1}$）可分别减少阿维菌素和呋虫胺有效成分用量20%和60%，减药效果显著。然而，阿维菌素原药微溶于水，其常规剂型多以甲苯、二甲苯为助溶剂，对环境不友好；且在紫外光下易降解，导致原药利用率低[16]。呋虫胺作为第三代烟碱类杀虫剂，已成为杀虫剂市场的中坚力量，但多次报道该药剂对蜜蜂等环境生物有较强急性毒性[17-18]。

农药缓控释技术通过将有效成分包裹在天然或合成高分子材料中，达到控制释放、提高有效成分利用率的目的，与常规剂型相比其持效期长、急性毒性弱、稳定性更好[19-20]。笔者在本研究中所用2.25%阿维菌素•呋虫胺双载纳米微囊缓释剂以聚乳酸（PLA）为载药体系，平均粒径245.7 nm，载药量39.1%，其中阿维菌素和呋虫胺含量分别为8.2%∶30.9%（有效成分比1∶3.8），具有优良的分散性和稳

定性，使用该剂型防治梨树梨小食心虫可延长施药间隔期15 d以上[13]。笔者在本研究中也发现，使用2.25%阿维菌素•呋虫胺双载纳米微囊缓释剂二次药后15 d对苹果黄蚜的防效已超常规剂型，且仍然维持在较高水平，推荐用于苹果黄蚜早期防治。尤其是苹果树生长周期长，常规化学防治方案用药次数多、药剂利用率低，在该防控场景下，推广应用农药缓释剂型对果品安全生产具有现实意义。

## 4 结 论

鉴于2.25%阿维菌素•呋虫胺双载纳米微囊缓释剂对环境友好且持效期长，推荐最佳使用时间为苹果黄蚜始发期，与助剂GY-T1602配合使用，连续用药两次为宜；在苹果黄蚜高发期推荐使用5%阿维菌素乳油与20%呋虫胺可溶粒剂1∶4混配后添加助剂GY-T1602使用，可快速压低虫口密度以获得更好的速效性。

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