

# The Jekyll and Hyde case of *Nesidiocoris tenuis* (Reuter) in the management of *Bemisia tabaci* (Gennadius) on tomato plants under greenhouse conditions

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## Research Article

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# Abstract

The rise of *Nesidiocoris tenuis* (Reuter) as a natural enemy of various greenhouse pests in protected systems is widely reported around the globe, mainly in the Mediterranean basin, Asia, and North and Central America. *In-vitro* studies on improving its growth and reproduction using artificial and factitious diets, and banker plants for its breeding and propagation, and the use of violet-light (LEDs) as the attraction mechanism are well established. However, field studies are lacking in integrating these biological control components to promote *N. tenuis* predation on greenhouse pests. First, we performed toxicity assays *in-vitro* and in field conditions. Results revealed that neonicotinoids and spinosyns were toxic to *N. tenuis*. Avermectins & milbemycins, pyridine azomethine derivatives and diamides, in contrast, were less to moderately toxic against *N. tenuis* but toxic to *Bemisia tabaci*, a known, widespread greenhouse pest. Field tests under greenhouse conditions were performed to evaluate the role of violet-LEDs in relocating *N. tenuis* from banker plants to tomato plants and their augmentative effect on the densities of *B. tabaci*. Results showed that the movement of *N. tenuis* from banker plants to tomato plants was accelerated when supplemented with violet-LEDs. The accelerated resettlement of *N. tenuis* on tomato plants aided by selective pesticides significantly reduced *B. tabaci* egg, nymph and adult densities, densities that were relatively the same compared to those of the greenhouse with conventional pest control strategies. Overall, comparable outcomes in managing a pest are possible when biological control agents are integrated with environmentally safe and cost-effective approaches.

## Key Message

- *Nesidiocoris tenuis* and its role as natural enemy of greenhouse pests is globally known. However, its compatibility with pesticides and its augmentation with biological control components in field studies are still lacking.
- Neonicotinoids and spinosyns were relatively toxic to *tenuis* nymphs and adults.
- Avermectins & milbemycins, pyridine azomethine derivatives and diamides are less to moderately toxic against *tenuis* but toxic to greenhouse pest, *Bemisia tabaci*, therefore, can be used as selective pesticides to augment *N. tenuis*.
- Violet-LEDs enhanced relocation and establishment of *tenuis* from banker plants to tomato plants
- The successful *tenuis* reestablishment aided with selective pesticides suppressed *B. tabaci* densities.

## Introduction

Integrated pest management (IPM) is a set of biological control components combined to maintain a pest population at levels below economic-threshold levels while conserving or promoting beneficial insects such as natural predators (Barzman et al. 2015). Successful integration of natural predators with other biological control components depends on thorough evaluation of biological control components that are involved in promoting natural predators. Biological control components such as banker plants, insectary plants, artificial diets, pheromones and et cetera have so far been documented to play a role in

maximizing the predation potential of natural predators (NARO, 2019). In the Mediterranean agroecosystems, natural predators such as *Macrolophus pygmaeus* Rambur, *Dicyphus maroccanus* Wagner, *Nesidiocoris tenuis* Reuter (Hemiptera: Miridae), predatory mite *Amblyseius swirskii* Athias-Henriot (Acari: Phytoseiidae) and the minute pirate bug *Orius laevigatus* Fieber (Hemiptera: Anthocoridae) have been shown to be effective in controlling small arthropod pests such as sweet potato whitefly *Bemisia tabaci* Gennadius (Hemiptera: Aleyrodidae), the western flower thrips *Frankliniella occidentalis* Pergande (Thysanoptera: Thripidae) and aphids *Myzus persicae* Sulzer, *Aphis gossypii* Glover, *Macrosiphum euphorbiae* Thomas, and *Aulacorthum solani* Kaltenbach (Hemiptera: Aphididae) (Sanches 2008; Calvo et al. 2009; Perez-Hedo and Urbaneja, 2015). In North America, the native species, *Dicyphus hesperus* Knight, is commercially available and is used in temperate areas of Canada, Northern USA, and recently in Mexico to control several pests of tomato cultivated in greenhouses (Shipp and Wang, 2006; Calvo et al. 2016; Perez et al. 2020). In Asia, extensive studies have been in progress in the utilization of *N. tenuis* to control greenhouse pests such as whiteflies and aphids (Nakaishi et al. 2011; Nakano et al. 2016; Uehara et al. 2019; Yano et al. 2020; Owashi et al. 2019; Park and Lee, 2021).

Pesticides are an essential arm of IPM. Pest management using pesticides has been a success for many years, yielding satisfactory results. The success in managing pests with pesticides, however, is marred by high running costs of commercially mass-produced chemical insecticides, development of pest resistance and secondary outbreak of other pests, to name a few. Associated with the discussion at hand, pesticides can be toxic to the environment, to biological control agents such as natural predators, and to parasitoids. For pesticides and biological control agents to work effectively, selective or compatible pesticides are proposed. Choosing a selective or a compatible insecticide or selectively applying the pesticides are essential decisions in managing the given pest, at the same time preserving the biological control agents. However, choosing a selective or a compatible insecticide is a matter of gains and losses, pest status and its economic importance, labor and cost of control and the impact on the environment (Torres and Bueno, 2018). The prospect of using selective/compatible pesticides in combination with biological control agents is on the rise. In theory, chemical compounds, when used in combination with an effective natural enemy, may provide more comprehensive prophylactic and remedial treatments (Gentz et al. 2010). However, comprehensive studies are required to fully grasp the compatibility of insecticides and natural enemies for better results than either approach alone.

*Nesidiocoris tenuis*, a zoophytophagous mirid bug can prey on a variety of greenhouse pests such as whiteflies, aphids, thrips and some lepidopterans (Ghoneim, 2014). Previous reports have shown the use of *N. tenuis* as a natural enemy for major tomato pests such as tomato borer (Urbaneja et al. 2009) and whiteflies (Calvo et al. 2012). However, due to its zoophytophagous nature, *N. tenuis* also plant feeds when prey is scarce (Calvo et al. 2009). Damage to plants is expected from zoophytophagous mirid bugs, but the damage is always compensated for by the gain in pest suppression (Biondi et al. 2016). Previous studies have reported the integration of *N. tenuis* with biological control components to augment *N. tenuis* in suppressing greenhouse pests while feeding less on plants. To name a few, these include the use of resistant crops mediated by endophytic strain of *Fusarium solani* K that reduce *N. tenuis* plant feeding (Garantonakis et al. 2018); optimizing the initial density of *N. tenuis* when released to minimize

plant feeding (NARO, 2019) and use of bunker plants for *N. tenuis* to breed and reproduce on (Huang et al. 2011). The use of banker plants has been successful in promoting *N. tenuis* breeding and proliferation, however, relocation from banker plants to crops is somewhat delayed as *N. tenuis* prefers banker plants to the crops (Saito et al. 2021). This delay in commercial crop production can be catastrophic if initial pest density is not managed. Several studies in the last decade have showed a spectrum of wavelength preferences that natural predators respond to (Shimoda and Honda, 2013; Ogino et al. 2016). Uehara et al. (2019) then investigated whether *N. tenuis* has a particular spectral preference. Their results showed that *N. tenuis* mostly preferred the violet light wavelength (peaking at 405nm). However, field studies are lacking to show the effectiveness of violet light as *N. tenuis* attraction and relocation mechanisms.

Tomato production in Japan is almost always under greenhouse conditions. However, tomato production is always marred by *B. tabaci* through herbivory damage and vectoring of viral diseases such as Tomato yellow leaf curl virus (TYLCV) and Tomato Chlorosis virus (ToCV). While pesticides are recommended for effective control, high costs and detrimental impacts on the surrounding environment and the natural enemies used in neighboring fields, as such, alternative means are being demanded by tomato farmers (Wari et al. 2020; Saito et al. 2021). In this study, we determine (i) the compatibility of insecticides and fungicides with *N. tenuis* by testing the toxicity and optimum lethal dose (LD<sub>50</sub>) of the pesticides against different growth stages of *N. tenuis*; (ii) promotion of *N. tenuis* proliferation on banker plants; (iii) assess the movement of *N. tenuis* from banker plants to tomato plants when aided by a natural enemy attraction violet light-emitting diodes (hereafter as violet-LEDs); and (iv) the collective effect of *N. tenuis*, banker plants, violet-LEDs and selective pesticides on the population densities of *B. tabaci*.

## Materials And Methods

### Plants and insect propagation

Verbena cuttings (*Verbena terena* cv. Tapian) (Agri-soken Inc. Ibaraki, Japan), Sesame seeds (*Sesamum indicum*) (Sakata Seed Garden Center Ltd. Kanagawa, Japan) and Cleome plantlets (*Cleome spinosa*) (Proven Winners North America LLC. Illinois, USA) were propagated in the glasshouse at Ibaraki Horticultural Research Institute. Tomato seeds (Takii Seed Co., Ltd.) of Momotaro Peace cultivar, a TYLCV tolerant cultivar were used all throughout in the field studies. *Nesidiocoris tenuis* populations, supplied by Agri-soken Inc. (Ibaraki, Japan) were reared on verbena, sesame, and cleome at Ibaraki Horticultural Research Institute insectary rooms under optimized conditions (25 ± 1°C, 65 ± 10% RH, and 16:8 L:D photoperiod). *Bemisia tabaci* populations were originally collected from capsicum fields in Kamisu City (Ibaraki Prefecture, Japan) in 2011 and were sparingly maintained on eggplants (*Solanum melongena*), kidney bean (*Phaseolus vulgaris* L.), and green bell pepper (*Capsicum annuum*) as a food source at Ibaraki Horticultural Research Institute insectary following the methods described in Wari et al. (2020).

### Insecticides and fungicides

Eighteen insecticides and five fungicides registered in the management of tomato pests and diseases in Ibaraki Prefecture were used in this study. Pesticides were prepared as per the agriculturally recommended dosage for bioassays and field applications rates (See Table S1).

## Bioassays

### *Nesidiocoris tenuis* toxicity assays

Mortality rates of *N. tenuis* nymph and adult assays and lethal dosage toxicity assays were performed essentially as described in Wari et al. (2021). In brief, 15-20 *N. tenuis* nymphs and adults were offered to *artemia* cysts contaminated with pesticides and incubated under laboratory conditions of  $25\pm 1^\circ\text{C}$ ,  $65\pm 10\%$  RH and 16:8 L:D photoperiod. Seventy-two hours later, dead or alive individuals were assessed by touching them with a brush. No movement was considered dead. The mortality rate for each pesticide was corrected using Abbott's formula (Abbott, 1925). Each insecticide treatment had three replicates. Insecticides mainly registered for *B. tabaci* control in tomato production (neonicotinoids, spinosyns, avermectins and milbemycins, pyridine azomethine derivatives and diamides) were further tested for their  $\text{LD}_{50}$  against *N. tenuis* nymphs and adults. Mortality rates were calculated from the series of concentrations and lethal dose determined.

Furthermore, potted assays were performed in semi-greenhouse conditions to mimic the movement of *N. tenuis* from banker plants to tomato plants after having been sprayed with pesticides. First, *N. tenuis* were released onto the banker plants (*V. terena* cv. Tapian, *S. indicum* and *C. spinosa*) that had been cultivated in the greenhouse. Six weeks later, 6-week-old tomato seedlings were sprayed with pesticides and placed on a mesh bench adjacent to banker plants with *N. tenuis*. Violet-LEDs were then set behind the tomato seedlings to attract *N. tenuis* adults from the banker plants to the tomato seedlings. The number of *N. tenuis* adults (not dead) on tomato seedlings reared with different pesticides and at different concentrations were quantified after 3, 6, 10 and 18 days. After every count at 3, 6 and 10 days, tomato seedlings were randomly repositioned from their previous position to allow random movement of *N. tenuis* from the banker plants when attracted to the violet-LEDs. Six tomato seedlings were used as replicates for each pesticide.

### *Bemisia tabaci* adult and nymph toxicity assays

Mortality rates of *B. tabaci* nymphs and adult assays were performed as described in Wari et al. (2020). In brief, 15-20 *B. tabaci* adults were subjected to *Capsicum annum* leaves leaf-dipped into insecticide solutions. Each insecticide treatment had four biological replicates. After 72 hours, living or dead adults were tallied, and mortality rate computed using Abbott's formula (Abbott, 1925). *Bemisia tabaci* nymphs, on the other hand, was assayed on *Phaseolus vulgaris* plants. *Bemisia tabaci* adults were first allowed to lay eggs on the underside of the *P. vulgaris* leaves, and once the eggs reached 2<sup>nd</sup> instar stage, bioassays were performed. *Phaseolus vulgaris* leaves containing the *B. tabaci* 2<sup>nd</sup> instar nymphs were leaf-dipped, air dried then placed in the incubator under laboratory conditions. After 6 to 7 days, 2<sup>nd</sup> instar nymphs

progressing to 4<sup>th</sup> instar nymphs were quantified, and mortality rate computed using Abbott's formula (Abbott, 1925). Two broad leaves of the 2-week-old *P. vulgaris* plants halved by the mid-vein yielding four halves were used as four replicates.

## **Field tests; integrating *N. tenuis* with biological control components and selective pesticides**

### *Experimental treatment*

Field test treatments in this study are as follows; (i) IPM treatment, (ii) semi-IPM treatment, (iii) banker plants treatment, (iv) positive control, and a (iv) negative control treatment. IPM treatment included the integration of *N. tenuis* with banker plants, violet-LEDs and selective pesticides. Semi-IPM treatment involved *N. tenuis* with banker plants and violet-LEDs but without selective pesticides. Banker plants treatment was set up as a negative control treatment to IPM and semi-IPM treatments to assess and compare the movement of *N. tenuis* from banker plants to tomato plants. Banker plants treatment included *N. tenuis* and banker plants only but without violet-LEDs and selective pesticides. Positive control treatment consisted of synthetic pesticides, both selective and non-selective, that were sprayed routinely to control *B. tabaci* populations (See Table S2 for pesticide type and date of pesticide application). To verify the role of *N. tenuis* and the biological control components with selective pesticides against *B. tabaci* densities, a negative control treatment with no pest control means but *B. tabaci* only was included.

### *Greenhouse preparations and experiment settings*

Field studies were performed in two consecutive years, 2019 and 2020. The experiments were conducted in the Ibaraki Horticultural Research Institute inside 10 m by 5 m vinyl pipe greenhouses. Greenhouse preparations, tomato seed sowing and transplantation are as described in Wari et al. (2020) and Saito et al. (2021). In brief, three weeks after transplanting tomato seedling and banker plants, *N. tenuis* and *B. tabaci* were released. *Nesidiocoris tenuis* nymphs and adults were released directly onto the banker plants (and not onto tomato seedlings) for IMP, semi-IPM and banker plants treatments at a rate of 0.5 individual per tomato seedling while *B. tabaci* adults were randomly released onto tomato seedlings in all treatments at a rate of 1 individual per tomato seedling. *Nesidiocoris tenuis* and *B. tabaci* survey started four weeks after the *N. tenuis* and *B. tabaci* were released. Pesticide type and application schedule for positive control treatment and IPM treatment greenhouse are as shown in Table S2 and S3, respectively. Only selected pesticides that showed moderate to no toxic effect on *N. tenuis* were selected and applied in the IPM treatment. Pesticide application in positive control treatment included all synthetic pesticides, irrespective of selective or non-selective, were applied on a weekly basis to control *B. tabaci* populations.

### *Sampling and quantification of test subjects*

Quantification of *N. tenuis* individuals on tomato and banker plants are essentially as discussed in Saito et al. (2021). In brief, *N. tenuis* nymphs and adults on tomato plants were quantified by visually scanning each tomato plant. *Nesidiocoris tenuis* nymphs and adults on the underside and topside of tomato

leaves, as well as on the flower stalks and shoots, were counted and recorded. To minimize errors in quantifying *N. tenuis* on tomato plants, as adults are prone to disperse when disturbed, disturbance of tomato plants was minimized. Furthermore, the entire counting was performed by one person for consistency and to keep track of the *N. tenuis* movement. To assess the relocation of *N. tenuis* individuals, tomato plants in each greenhouse were clustered in four zones. *Nesidiocoris tenuis* nymph and adult counts for each of the zones (10~12 tomato plants per zone) were pooled together and the average computed to represent each zone. To determine the population densities of *N. tenuis* on tomato plants in each treatment throughout the study period, *N. tenuis* (both nymph and adult) counts from all tomato plants (40~48 tomato plants per greenhouse) were pooled together and the average calculated to represent the number of *N. tenuis* per tomato plant. The averages for each sampled week (among zones and all plants in each treatment) were treated as replicates for each treatment per annual study. *Nesidiocoris tenuis* on the banker plants was quantified by placing a 40 cm by 20 cm white bath container 10-15 cm beneath the banker plants. The banker plants were then taped ten times. *Nesidiocoris tenuis* nymphs and adults that fell onto the white bath container were quantified and recorded as representative of the respective banker plants in a treatment and of the particular sampling period. Sampling of *N. tenuis* on banker plants were performed separately for each of the banker plants i.e. verbena, cleome and sesame.

*Bemisia tabaci* eggs, nymphs, and adults were quantified following the methods described by Wari et al. (2020) and Saito et al. (2021). In brief, twenty leaves per treatment were sampled every week. Eggs and nymphs (including 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup>, and 4<sup>th</sup> instar nymphs) on the underside of the tomato leaves were counted using a Leica S6E stereo microscope mounted with a Leica KL300 LED illumination. *Bemisia tabaci* egg and nymph counts for the twenty leaves were pooled together and the average calculated to designate the *B. tabaci* egg and nymph counts per tomato leaf in a given treatment. The averages for each sampled week were treated as replicates for each treatment per annual study. One 200 cm<sup>2</sup> yellow sticky trap (Arysta Lifesciences, Tokyo, Japan) was set in the middle of each treatment and collected after three days to determine *B. tabaci* adult population. Sticky traps setting and collection (together with leaves) were performed on a weekly basis for 13 consecutive weeks. After leaf and sticky trap sampling, pesticides were applied in the positive control and IPM treatment as per the application schedule in Table S2 and S3.

## Statistical analyses

*Nesidiocoris tenuis* (nymphs and adults) and *B. tabaci* (eggs, nymphs and adults separately) counts were tested for normality (Shapiro–Wilk test and Lilliefors test) and homogeneity (Bartlett's Test) using open-source software OpenStat (<http://openstat.info/OpenStatMain.htm>). The total number of *N. tenuis* (nymphs and adults) and *B. tabaci* eggs, nymphs and adults were then transformed logarithmically using 'x + 1' to meet the assumptions of analysis of variance (ANOVA). The effects of 'treatments (banker plants, semi-IPM and IPM)' and 'sampling interval (weeks)' factors and their interaction on the densities of *N. tenuis* on tomato, as well as the effect of banker plants on the abundance of *N. tenuis* on tomato plants were analyzed using repeated-measures ANOVA. Similarly, the effect of *N. tenuis* on *B. tabaci* egg,

nymph and adult densities was analyzed using a repeated-measures ANOVA model with treatment and sampling interval considered as fixed factors. *Nesidiocoris tenuis* distribution among the zones in the greenhouses between the banker plants, semi-IPM and IPM were analyzed using contingency chi-square test for two-way tables to test the relationship between treatments and zones. Furthermore, standard deviations (SD) were calculated from the mean of pooled data (40~48 tomato plants per greenhouse for *N. tenuis* counts per treatment, 10~12 tomato plants per zone for *N. tenuis* counts per zone, 20 tomato plant leaves per treatment for *B. tabaci* eggs and nymphs, and one 200 cm<sup>2</sup> yellow sticky trap per treatment for *B. tabaci* adults) per sampled week from two annual studies to represent the differences between the years.

## Results

### *Pesticide toxicity against N. tenuis*

To determine if insecticides registered for *B. tabaci* management in tomato production under greenhouse conditions can be toxic or harmless to *N. tenuis*, *in-vitro* toxicity assays were performed. Eight insecticides were tested against nymphs and adults of *N. tenuis* and *B. tabaci*. Results showed that dinotefuran, spinetram and abamectin at the agriculturally recommended dose, were moderately toxic to very toxic to nymphs and adults of both *N. tenuis* and *B. tabaci* with over 50 to 100% mortality rates (Table 1). Milbemectin, lepimectin, pyrifluquinazon and cyantraniliprole were toxic to *B. tabaci* nymphs and adults with over 70% mortality rate, however, less toxic to nymphs and adults of *N. tenuis* with mortality rates less than 50% (Table 1). Flonicamid was observed to be less toxic to nymphs and adults of both *N. tenuis* and *B. tabaci* (Table 1).

To further substantiate these results, median lethal dose (LD<sub>50</sub>) was determined for each insecticide. Results showed that LD<sub>50</sub> for dinotefuran (21 and 1000 folds for nymphs and adults respectively), acetamiprid (1.5 and 25 folds for nymphs and adults respectively), spinosyns (1.6 and 26 folds for nymphs and adults respectively), abamectin (9 and 66 folds for nymphs and adults respectively) and emamectin benzoate (5 and 9 folds for nymphs and adults respectively) were less than the agriculturally recommended dose (Table 2) affirming the high toxicity against *N. tenuis* nymphs and adults as shown in Table 1 (and Table 3 for acetamiprid and emamectin benzoate). LD<sub>50</sub> for milbemectin (293 and 201 folds for nymphs and adults respectively), pyrifluquinazon (672 and 1110 folds for nymphs and adults respectively) and cyantraniliprole (6854 and 922 folds for nymphs and adults respectively) higher than the agriculturally recommended dose (Table 2) affirming their reduced toxicity against *N. tenuis* nymphs and adults as shown in Table 1. Lepimectin, on the other hand, showed LD<sub>50</sub> values 4 folds less than the agriculturally recommended dose against *N. tenuis* nymphs but 3.5 folds higher than the agriculturally recommended dose against the adults, inconsistent with the toxicity assays shown in Table 1. Furthermore, pot-assays in semi-field conditions also revealed that non-to-fewer *N. tenuis* adults (0 to 0.2±0.5 per seedling) preferred tomato seedlings sprayed with dinotefuran, spinetoram and milbemectin relative to abamectin, lepimectin, pyrifluquinazon, cyantraniliprole and flonicamid (Table S4). These

results suggest that dinotefuran and spinetoram are toxic to *N. tenuis* nymphs and adults and therefore, incompatible to be integrated with *N. tenuis*. Abamectin, milbemectin and lepimectin showed inconsistent but moderate toxic effects in the *in-vitro* assays as well as potted-assays against *N. tenuis*. Furthermore, abamectin, milbemectin, lepimectin and emamectin benzoate were observed to be toxic to *B. tabaci*. Therefore, these insecticides can be used as *N. tenuis* suppressants when *N. tenuis* densities are beyond threshold limits at the same time, control *B. tabaci*. Pyrifluquinazon and cyantraniliprole showed toxicity with high mortality rates against *B. tabaci* but less toxic to *N. tenuis*. Thus, pyrifluquinazon and cyantraniliprole can be good candidates to be integrated with *N. tenuis* as selective pesticides.

Insecticides and fungicides registered for managing pests and diseases other than *B. tabaci* were also tested for their toxicity against *N. tenuis*. Results showed that acetamiprid and emamectin benzoate mostly used for managing aphids and leaf miners, respectively, and fluxametamide for multiple pests, were highly toxic to nymphs and adults of *N. tenuis* with mortality rates over 70% to 100% (Table 3). Chlorfenapur, registered to control cotton ballworm in tomatoes, was less toxic to *N. tenuis* nymphs ( $11.1 \pm 7.5$ ) but moderately toxic to the adults ( $56.0 \pm 18.1$ ) (Table 3). Lufenuron, bifenazate and spirotetramat registered in tomato production for spider mite control, tetraniliprole for managing thrips, fluometokin for other related pests and acetylated glyceride, a recently registered compound as a repellent and antifeedant of whiteflies, all have showed to be less toxic to both the nymphs and adults of *N. tenuis* (Table 3). Furthermore, pot-assays revealed that *N. tenuis* adults were observed on tomato seedlings sprayed with emamectin benzoate, chlorfenapyr, lufenuron, bifenazate, spirotetramat, tetraniliprole and furometokin three days post-treatment and increased as the survey continued. Brief occurrence of *N. tenuis* adults was noted six days post treatment for fluxametamide and 10 days post treatment for acetamiprid but no *N. tenuis* adults were detected thereafter (Table S4). Fungicides registered for powdery mildew management in tomato produced under greenhouse conditions were also tested for their toxicity on *N. tenuis* nymphs and adults *in-vitro* and in potted-assays. Results showed that the five fungicides were not toxic to the nymphs and adults of *N. tenuis in-vitro* (Table 3) and in potted-assay (Table S6). These results suggest that insecticides registered for pest control other than *B. tabaci*, acetamiprid and fluxametamide are incompatible with *N. tenuis* while emamectin benzoate and chlorfenapur can only be options when leaf miners and cotton ballworm are beyond economic threshold limits. Fungicides registered for powdery mildew control can be used in conjunction with *N. tenuis* when powdery mildew and other related fungal disease incidences are detected.

#### *Relocating N. tenuis on tomato plants using violet-LEDs*

To determine if *N. tenuis* can successfully establish on tomato plants when attracted by violet-light (in the form of violet-LEDs) from the banker plants, the movement of *N. tenuis* was assessed weekly. According to Uehara et al. (2019), *N. tenuis* become active during the dusk, therefore, violet-LEDs were connected to an automatic switch that switched on the violet-LEDs from 5:00 pm and off at 8:00 pm, to coincide with dusk. The greenhouse was divided into four zones, zone 1 adjacent to banker plants and zone 4 by the violet-LEDs. The movement of *N. tenuis* from banker plants towards the violet-LEDs was assessed by quantifying *N. tenuis* individuals on each tomato plant. The number of *N. tenuis* individuals on each

tomato plants in a zone is summed and showed as percentage, as shown in Fig. 1 (nymphs and adults combined), Fig. S1A, B and C (adults only) and Fig. S1D, E and F (nymphs only). Results showed that *N. tenuis* relocated from banker plants and onto tomato plants and scattered among tomato plants in all zones in semi-IPM and IPM treatments with violet-LEDs. On the other hand, *N. tenuis* in banker plants treatment (where no violet-LEDs were installed) were mainly situated in zone 1 in the first two weeks of the survey. This is evident as *N. tenuis* counts were highly significantly different ( $p = <0.001$ ) between the violet-LED equipped treatments (IPM and semi-IPM) and no violet-LED equipped treatment (banker plants) as well as between the zones from week one of the survey until week nine (Table 4). *Nesidiocoris tenuis* individuals detected on tomato plants in the three treatments were mainly of the adults (Fig. S1A, B and C). *Nesidiocoris tenuis* nymphs were detected 8 weeks later from the time they were released in banker plants treatment, 6 weeks later for semi-IPM treatment and 5 weeks later in the IPM treatment, respectively (Fig. S1D, E and F). Furthermore, in the banker plants only treatment, *N. tenuis* distribution in all four zones became apparent in the tenth week from the start of the survey ( $p = >0.05$ ) (Table 4) (Fig. 1). These observations suggest that violet-lights are essential and effective in accelerating the relocation of *N. tenuis* from banker plants and successfully establishing on tomato plants, where pests are usually found.

#### *Densities of N. tenuis on tomato and banker plants*

To assess how the *N. tenuis* population established and shifted on tomato plants after relocating from banker plants aided by violet-LEDs, the number of *N. tenuis* individuals (nymphs and adults included) per tomato plant was determined. The population trends of *N. tenuis* on tomato plants are shown in Fig. 2A. Gradual increase in the number of *N. tenuis* in semi-IPM and IPM treatment relative to the *N. tenuis* trend in banker plants treatment was observed. All the same, a significant increase in *N. tenuis* during post-release was observed on tomato plants in the three treatments. However, the onset of the increase was significantly earlier in semi-IPM and IPM treatment than in banker plants treatment, leading to the significant interaction in the sampling interval ( $p = <0.001$ ) (Table 5). The significant increase in the number of *N. tenuis* per tomato plant in semi-IPM and IPM rose until week 7 of the survey until the population trends of *N. tenuis* in IPM dropped briefly. The drop can be attributed to the application of pyrifluquinazon (Table S3). *Nesidiocoris tenuis* densities in semi-IPM progressively increased, while *N. tenuis* densities in banker plants treatments commenced to gradually decline while *N. tenuis* numbers in IPM began to steadily rise, leading to the highly significant interaction between the three treatments ( $P < 0.001$ ).

*Nesidiocoris tenuis* on banker plants (sum of *N. tenuis* nymphs and adults in the three banker plants; verbena, sesame and cleome) gradually increased as the study progressed, reaching maximum peak for banker plants only ( $328.0 \pm 63.5$ ) and semi-IPM ( $324.0 \pm 38.4$ ) treatments at the eleventh week from the time they were released onto the banker plants (Fig. 2B). The *N. tenuis* on the banker plants in IPM treatment however, reached its maximum peak ( $410.5 \pm 35.0$ ) one week ahead of banker plants only and semi-IPM treatments (Fig. 2B). Different cultivation practices did not have any effect on the *N. tenuis* densities on the three banker plants combined ( $p = 0.821$ ) (Table 5). The sum of the three banker plants

yielded increased number of *N. tenuis* (nymphs and adults), however, *N. tenuis* densities on individual banker plants showed that *N. tenuis* preferred sesame and cleome, rather than verbena (Fig. S2).

The effect of violet-LEDs was evident as the densities of *N. tenuis* on banker plants in semi-IPM were not significantly different from those on the tomato plants ( $p = 0.052$ ) (Table 5) compared to the banker plants treatment, in which *N. tenuis* densities were higher in banker plants but very few moving to tomato plants ( $p = 0.026$ ) (Table 5, Fig. 1 and Fig 2A). On the other hand, *N. tenuis* densities on banker plants in IPM treatment were significantly different to those on the tomato plants ( $p = <0.001$ ) (Table 5). The differences observed here as compared to semi-IPM can be due to the selective pesticides applied in IPM treatment (Table S3), as a result leading to a significant interaction in the sampling interval ( $p = <0.001$ ) (Table 5).

### *Integrated effect of N. tenuis, biological control components and selective pesticides on different growth stages of B. tabaci*

To determine if the augmentative impact of natural enemy, banker plants, violet-lights (violet-LEDs), and selective pesticides (IPM treatment) on the densities of *B. tabaci*, different growth stages of *B. tabaci* eggs, nymphs and adults were surveyed. To validate the effect of *N. tenuis* integrated with biological control components (i.e., IPM treatment), a positive control treatment with vigorous pesticides usage and a negative control treatment with no control means to control *B. tabaci* under greenhouse conditions were included. There were significant differences in the augmentative effect of *N. tenuis* integrated with banker plants, violet-LEDs and selective pesticides (IPM treatment) on *B. tabaci* compared to semi-IPM treatment (*N. tenuis*+banker plants+violet-LEDs) (nymphs:  $p = 0.036$  and adults:  $p = 0.022$ ), banker plants treatment (*N. tenuis*+banker plants) (eggs:  $p = 0.049$ ; nymphs:  $p = 0.040$  and adults:  $p = 0.002$ ) and negative control treatment (*no pest control means*) (eggs:  $p = 0.007$ ; nymphs:  $p = 0.001$  and adults:  $p = 0.019$ ) (Table 6). On the other hand, no significant difference was observed between the IPM treatment and positive control (conventional greenhouse) on *B. tabaci* eggs ( $p = 0.643$ ), nymphs ( $p = 0.857$ ) and adults ( $p = 0.410$ ). The effects and interaction between the treatments and sampling intervals are reflective of the *B. tabaci* population trends shown in Fig. 3. These results demonstrate that *N. tenuis* when augmented with biological components such as banker plants to promote breeding and proliferation; violet-lights to enhance relocation from banker plants to tomato plants; and selective pesticides in managing *B. tabaci* growth stages that cannot be preyed on by the natural enemy, collectively can suppress *B. tabaci* incidences. However, further studies on the augmentative effect of *N. tenuis*, biological components, and selective pesticides on consecutive annual studies and in large scale systems is needed to categorically substantiate these results.

## Discussion

*Nesidiocoris tenuis* is both a beneficial natural enemy and a pest too, a foe and a friend, or as annotated by Ferguson et al (2020), a Jekyll and Hyde. In Japan, *N. tenuis* has been effectively integrated into the management of several greenhouse pests such as whiteflies and thrips on tomato plants (Nakano et al.

2016; Yano et al. 2020). While feeding damage on tomato plants is still unknown, NARO (2019) recommends that the initial number of *N. tenuis* to be released at the start of tomato cultivation at a rate of one *N. tenuis* individual per two tomato plants. Calvo et al. (2009) in their findings recommended one *N. tenuis* individual per tomato plant. According to two separate studies at two geographically different localities, it would be safe to assume that *N. tenuis* at a rate of 0.5 to 1 individual per tomato plant is enough to not cause any feeding damage that may result in significant economic losses. However, in time, *N. tenuis* can breed, proliferate and increase in numbers exceeding the recommended rates. And when prey becomes scarce, *N. tenuis* may tend to plant feed, resulting in damages to plants. To elucidate this dilemma, banker plants have been suggested. Banker plants are known for their role in promoting natural enemies to densities beyond threshold limits. With banker plants as the source base for natural enemies, and when cultivated together with crops, natural enemies can migrate to crops where pests are situated and begin pest feeding. Hypothetically, this is workable and can be an economically and environmentally viable solution for pest control. Nakano et al. (2016) in their three-year study showed that *N. tenuis* integrated with banker plants (*Verbena* × hybrida cv. Tapián) successfully colonized the tomato, however, the impact of *N. tenuis* on the population densities of *B. tabaci* could only be realized at the end of the cultivation period. They further showed that integrating *N. tenuis* with banker plants and selective pesticides somewhat impacted the rates of TYLCV, a viral disease vectored by *B. tabaci*, compared to conventional plots. They concluded that combining *N. tenuis* and banker plants can be effective in managing *B. tabaci* populations and as a result, inhibiting the spread of TYLCV. On the other hand, Uehara et al. (2019) postulated that supplementing *N. tenuis* with banker plants is innovative however, re-establishing *N. tenuis* on tomato plants can be difficult given that *N. tenuis* prefers banker plants more than the tomato plants. Similar observations were reported in our previous study (Saito et al. 2021). Uehara et al. (2019) further investigated different light spectrums as an attraction mechanism. They showed in laboratory and greenhouse conditions that while *N. tenuis* preferred banker plants more, when supplemented with violet-lights, *N. tenuis* relocated from banker plants and became evenly dispersed on tomato plants.

Expounding on Nakano et al. (2016) and Uehara et al. (2019) studies, we tested under greenhouse conditions the impact of integrating *N. tenuis*, banker plants, violet-lights and selective pesticides on the population densities of *B. tabaci*. Results showed that population densities of different growth stages of *B. tabaci* were no different to that of the chemical control treatment. Additionally, we also surveyed the occurrence of powdery mildew and TYLCV incidences during the study. Reduced powdery mildew and TYLCV incidences were observed in the IPM treatment compared to other treatments (Fig. S3A and B). Furthermore, all tomato plants in banker plants treatment showed necrotic rings (as result of *N. tenuis* feeding) nine weeks from the start of the study. In contrast, 50 per cent and less than 30 per cent in semi-IPM and IPM treatment, respectively, was observed 10 weeks from the start of the study (Fig. S3C). The zero occurrence of powdery mildew incidences in IPM and positive control greenhouses is the direct impact of fungicides sprayed sparingly during the study (Table S3 and Fig. 3A). Reduced but not complete inhibition of TYLCV incidences is attributable to the integrated impact of *N. tenuis*, acetylated glyceride and other selective pesticides in managing the densities of *B. tabaci* spreading the virus (Table

S3 and Fig. 3B). Furthermore, the decreased feeding damage on tomato plants (Fig. S3C) by *N. tenuis* can be associated with the selective pesticides (Table S3) maintaining low densities of *N. tenuis* on tomato plants (Fig. 2). Collectively, integrating natural enemies may broaden its efficacy to the target pest and the related pest and diseases that co-occur during the cultivation period.

As a zoophytophagous mirid bug, *N. tenuis* sustains itself by feeding on animals, and is also known to feed on plants or crops resulting in crop damage and yield losses (Arnó et al. 2010; Pérez-Hedo & Urbaneja, 2016; Sanchez, 2009; Sanchez & Lacasa, 2008). Even then, *N. tenuis* phytophagous behavior have been shown to induce herbivore-induced plant volatiles (HIPVs) which can help modulate pest and natural enemy locations, attract beneficial insects and deter pests (Bouagga et al. 2018; Pérez-Hedo et al. 2018). In the Mediterranean Basin, management of greenhouse pests compensates the feeding damage caused by *N. tenuis* (Bhatt & Patel, 2018; Pérez-Hedo et al. 2017). On the contrary, plant feeding damage caused by *N. tenuis* is more severe than the benefits it brings as a natural enemy, thus it has been considered a pest in the south of France (Trottin-Caudalet al 2006; Trottin-Caudal & Millot, 1997) and recently in Belgium and the Netherlands (Moerkens et al. 2020). *Nesidiocoris tenuis* being a beneficial natural enemy and a pest is still a controversy. However, the beneficial natural enemy to greenhouse pests is still practicable if augmented with biological control components and selective pesticides. Pesticides have always been the first line of defense particularly in large scale farming as profits always outweigh the running costs of the pesticides, let alone the many adverse effects on the environment, development of pesticide resistance and their impacts on beneficial insects. Nevertheless, not all pesticides are toxic to all kinds of insects. Adoption of newly developed insecticides that are selective (harmful to pests but non-toxic to beneficial insects) and their role in improving IPM systems have been widely reported (Orr, 2009). The use of selective pesticides is perhaps the most powerful tool by which pesticide use decisions can be modified to favor natural enemies (Hull and Beers, 1985), and the one most readily available to growers (Ruberson et al. 1998). Selecting the best insecticides for pest management that have minimal impacts on the beneficials can be challenging. If appropriately integrated with biological components and carefully tested and selected pesticides, *N. tenuis* densities can be maintained at acceptable threshold limits to control greenhouse pests and not cause economic damage on plants. While this is not an authentic means of pest control, and given that pest problems always evolve in time, additional research is regularly needed to perfect the *N. tenuis* integration into IPM programs.

Biological control and its role in pest management dates back to ancient times. Over the past couple of decades, biological control has flourished in a flush of optimism for a “silver bullet” (a simple and seemingly magical solution to a complicated problem) (Cock et al. 2016). These phenomena have prompted many to question if biological control is still a necessary, safe, and effective means of pest control (McEvoy and Coombs 2000). And then, there is the augmentation of biological control in IPM systems. Although not innovative in pest management technologies, there are always constraints to a successful augmentation of biological control and IPM. Besides, there are many varieties of options and prospects offered by natural enemies and the technology available to manage a vast and ever-increasing pest problems. Furthermore, societies’ concern for environmental and human safety, pollution, resistance to pesticides, and the high running cost of pesticide use suggests the need for an effective but safe and

cost-efficient means. Biological control augmented in IPM systems is one such instance that is already in motion but in need for fine-tuning, implementation and exposure to be adopted for general use. Pesticides, on the other hand, are an integral arm of IPM. While pesticides may have negative impacts on the environment and humans alike, pesticides are here to stay, as they play a major role in pest control. As such, a more environmentally and ecologically sound approach in using pesticides therefore, is a prerequisite and promotion of selective or guided pesticide use is a means forward into the future, if IPM system are to work effectively. *Nesidiocoris tenuis*, has been a success story in managing greenhouse pests across many countries. Although, it may be considered a controversial natural enemy in Europe, there are means by which its negative impact on plants can be corrected. Case in point, integrating *N. tenuis* with biological control components and properly supplemented with selective or guided pesticides, as shown in this study, can minimize the negative effects of *N. tenuis*, improve pest control, be safer to the environment, and generally a step forward in IPM advancement.

## **Declarations**

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### **Compliance with ethical standards**

### **Conflict of interest**

The authors declare no conflict of interests.

### **Ethics approval**

Not applicable

### **Consent to participate**

Not applicable

### **Consent for publication**

Not applicable

## Author Contributions

Conceptualization: DW, MT and TO; Methodology: DW, TS, MT, RO, TM, TT, MS and TO; Formal analysis and investigation: DW, TS, RO and TM; Writing - original draft preparation: DW; Writing - review and editing: DW, TS, MT, RO, TM, TT, MS and TO; Funding acquisition: MT, TM and TO; Resources: TT for the *N. tenuis* and banker plants, MS for LEDs.

## References

- Abbott, WS. A method of computing the effectiveness of insecticides (1925) *J Econ Entomol* 18:265–267. <https://doi.org/10.1093/jee/18.2.265a>
- Arno J, Gabarra R, Liu TX, Simmons AM, Gerling D (2010) Natural enemies of *Bemisia tabaci*: predators and parasitoids. In: Stansly PA, Naranjo SE (eds) *Bemisia* bionomics and management of a global pest. Springer, Dordrecht, pp 385–421
- Barzman M, Bàrberi P, Birch NE, Boonekamp P, Dachbrodt-Saaydeh S, Graf B, Hommel B, Jensen JE, Kiss J, Kudsk P, Lamichhane JR, Messéan A, Moonen AC, Ratnadass A, Ricci P, Sarah JL, Sattin M (2015) Eight principles of integrated pest management. *Agronomy for Sustainable Development* 35:1199–1215.
- Bhatt N, Patel MV (2018) Tomato bug, *Nesidiocoris tenuis* (Reuter): A zoophytophagous insect. *J Entomol Zool* 6:1550–1556. <https://doi.org/10.1007/s10526-012-9486-7>
- Biondi A, Zappalà L, Di Mauro A, Tropea Garzia G, Russo A, Desneux N, Siscaro G (2016) Can alternative host plant and prey affect phytophagy and biological control by the zoophytophagous mirid *Nesidiocoris tenuis*? *Biocontrol* 61:79–90. <https://doi.org/10.1007/s10526-015-9700-5>
- Bouagga S, Urbaneja A, Rambla JL, Flors V, Granell A, Jaques JA, Pérez-Hedo M (2018) Zoophytophagous mirids provide pest control by inducing direct defenses, antixenosis and attraction to parasitoids in sweet pepper plants. *Pest Manag Sci* 74:1286–1296. <https://doi.org/10.1002/ps.4838>
- Calvo FJ, Bolckmans K, Stansly PA, Urbaneja A (2009) Predation by *Nesidiocoris tenuis* on *Bemisia tabaci* and injury to tomato. *Biocontrol* 54:237–246. <https://doi.org/10.1007/s10526-008-9164-y>
- Calvo FJ, Lorente MJ, Stansly PA, Belda JE (2012) Preplant release of *Nesidiocoris tenuis* and supplementary tactics for control of *Tuta absoluta* and *Bemisa tabaci* in greenhouse tomato. *Entomol Exp Appl* 143:111–119. <https://doi.org/10.1111/j.1570-7458.2012.01238.x>
- Calvo FJ, Torres-Ruiz A, Velázquez-González JC, Rodríguez-Leyva E, Lomeli-Flores JR (2016) Evaluation of *Dicyphus hesperus* for biological control of sweet potato whitefly and potato psyllid on greenhouse tomato. *Biocontrol* 61:415–424. <https://doi.org/10.1007/s10526-016-9719-2>
- Cock MJ, Murphy ST, Kairo MT, Thompson E, Murphy RJ, Francis AW (2016) Trends in the classical biological control of insect pests by insects: an update of the BIOCAT database. *Biocontrol* 61:349–363.

<https://doi.org/10.1007/s10526-016-9726-3>

Ferguson KB, Visser S, Dalíková M, Provazníková I, Urbaneja A, Pérez-Hedo M, Marec F, Werren JH, Zwaan BJ, Pannebakker BA, Verhulst EC (2020) Jekyll or Hyde? The genome (and more) of *Nesidiocoris tenuis*, a zoophytophagous predatory bug that is both a biological control agent and a pest. *Insect Mol Biol. In press* <https://doi.org/10.1111/imb.12688>.

Garantonakis N, Pappas M, Varikou K, Skiada V, Broufas G, Kavroulakis N, Papadopoulou K (2018) Tomato inoculation with the endophytic strain *Fusarium solani* K results in reduced feeding damage by the zoophytophagous predator *Nesidiocoris tenuis*. *Front Ecol Evol* 6:1–7. <https://doi.org/10.3389/fevo.2018.00126>

Gentz MC, Murdoch G, King GF (2010) Tandem use of selective insecticides and natural enemies for effective, reduced-risk pest management. *Biol Control* 52:208–215. <https://doi.org/10.1016/j.biocontrol.2009.07.012>.

Ghoneim K (2014) Predatory Insects and Arachnids as Potential Biological Control Agents against the Invasive Tomato Leaf Miner, *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae): In Perspective and Prospective. *J Entomol Zool* 2: 52–71.

Huang N, Enkegaard A, Osborne LS, Ramakers PMJ, Messelink GJ, Pijnakker J and Murphy G (2011) The Banker Plant Method in Biological Control, *CRC Crit Rev Plant Sci*, 30:3, 259-278, <https://doi.org/10.1080/07352689.2011.572055>

Hull LA, Beers EH (1985) Ecological selectivity: Modifying chemical control practices to preserve natural enemies. In: Hoy, M.A. and Herzog, D.C. (eds), *Biological Control in Agricultural IPM Systems*. Academic Press, Orlando, FL, pp. 103–122.

McEvoy PB, Coombs EM (2000) Why things bite back: unintended consequences of biological weed control. In: Follett PA, Duan JJ (eds) *Nontarget effects of biological control*. Kluwer Academic Publishers, Boston, pp 167–194

Moerkens R, Pekas A, Bellinkx S, Hanssen I, Huysmans M, Bosmans L, Wackers F (2020) *Nesidiocoris tenuis* as a pest in Northwest Europe: Intervention threshold and influence of Pepino mosaic virus. *J Appl Entomol* 144:566–577. <https://doi.org/10.1111/jen.12789>

Nakaishi K, Fukui Y, Arakawa R (2011) Reproduction of *Nesidiocoris tenuis* (Reuter) on Sesame. *Jpn J Appl Entomol Zool* 55:199–205. <https://doi.org/10.1303/jjaez.2011.199> (in japanese with English abstract)

Nakano R, Tsuchida Y, Doi M, Ishikawa R, Tatara A, Amano Y, Muramatsu Y (2016) Control of *Bemisia tabaci* (Gennadius) on tomato in greenhouse by a combination of *Nesidiocoris tenuis* (Reuter) and banker

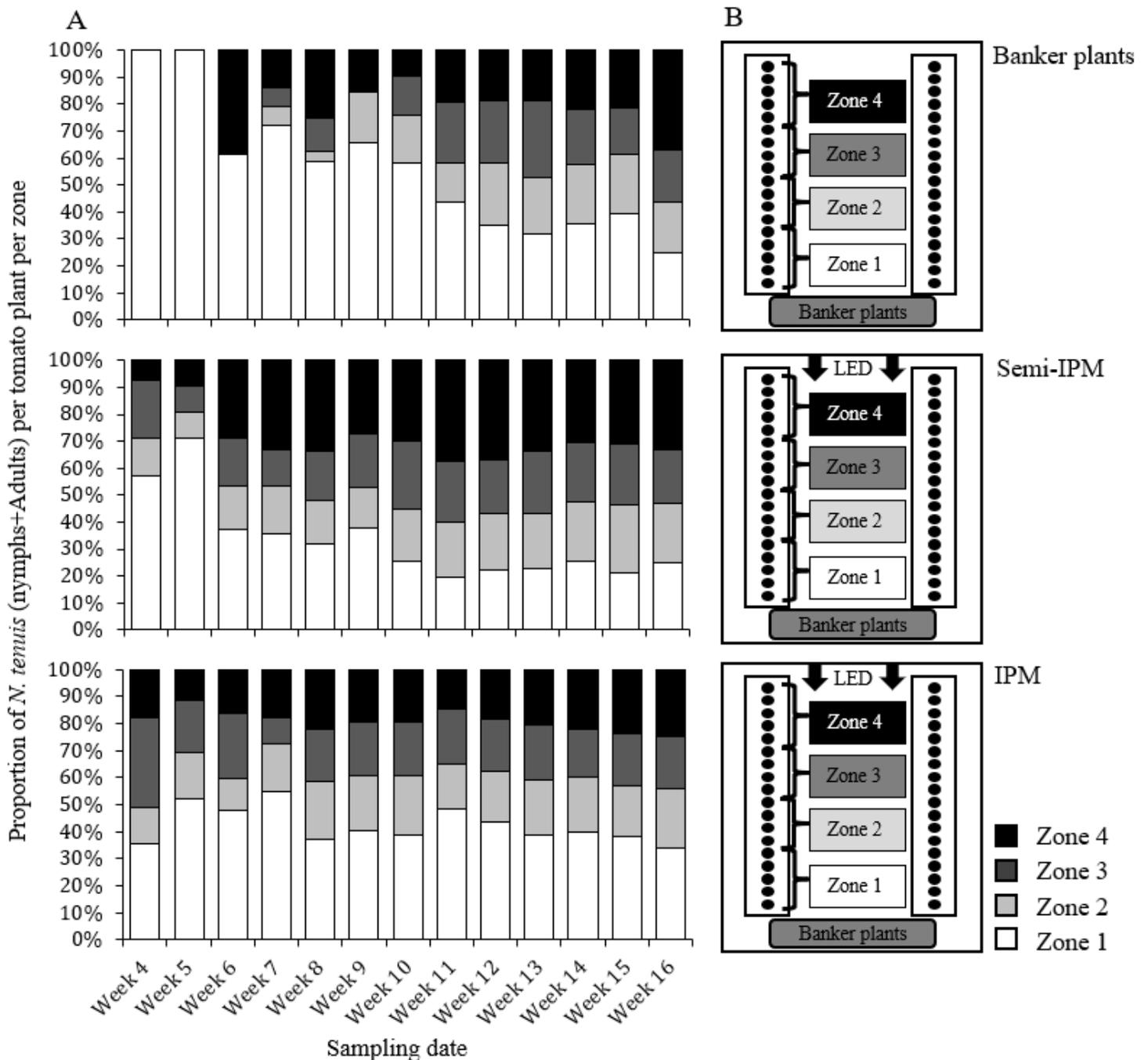
- plants. Ann Rep Kansai PI Prot 58:65–72 <https://doi.org/10.4165/kapps.58.65> (in Japanese with English abstract)
- NARO (2019) New manual for tomato pest control system that reduces the use of synthetic insecticides. (In Japanese) [https://www.naro.affrc.go.jp/publicity\\_report/publication/files/SIPtomatomanual190404-2205s.pdf](https://www.naro.affrc.go.jp/publicity_report/publication/files/SIPtomatomanual190404-2205s.pdf) (24th of August, 2020)
- Ogino T, Uehara T, Muraji M, Yamaguchi T, Ichihashi T, Suzuki T, Kainoh Y, Shimoda M (2016) Violet LED light enhances the recruitment of a thrip predator in open fields. Sci Rep 6:32302. <https://doi.org/10.1038/srep32302>
- Orr D (2009) Biological control and integrated pest management. In: Peshin R, Dhawan A (eds) Integrated pest management: innovation-development process. Springer, Dordrecht, pp 207–239
- Owashi Y, Hayashi M, Abe J, Kazuki M (2019) Effects of an alternative diet of Artemia cysts on the development and reproduction of *Nesidiocoris tenuis* (Hemiptera: Miridae). Appl Entomol Zool. 55: 121–127. <https://doi.org/10.1007/s13355-019-00660-y>
- Park YG, Lee JH (2021) UV-LED lights enhance the establishment and biological control efficacy of *Nesidiocoris tenuis* (Reuter) (Hemiptera: Miridae). PLoS ONE 16(1): e0245165. <https://doi.org/10.1371/journal.pone.0245165>
- Pérez-Hedo M, Urbaneja A (2015) Prospects for predatory mirid bugs as biocontrol agents of aphids in sweet peppers. J Pest Sci 88:65–73 <https://doi.org/10.1007/s10340-014-0587-1>
- Pérez-Hedo M, Urbaneja A (2016) The zoophytophagous predator *Nesidiocoris tenuis*: A successful but controversial biocontrol agent in tomato crops. Horowitz, A & Ishaaya, I., In: Advances in Insect Control and Resistance Management. Cham: Springer International Publishing, pp. 121–138.
- Pérez-Hedo M, Suay R, Alonso M, Ruocco M, Giorgini M, Poncet C, Urbaneja A (2017). Resilience and robustness of IPM in protected horticulture in the face of potential invasive pests. Crop Prot 97, 119–127. <https://doi.org/10.1016/j.cropro.2016.11.001>
- Pérez-Hedo M, Rambla JL, Granell A, Urbaneja A (2018) Biological activity and specificity of Miridae-induced plant volatiles. Biocontrol 63: 203–213. <https://doi.org/10.1007/s10526-017-9854-4>
- Pérez-Hedo M, Riahi C, Urbaneja A (2020) Use of zoophytophagous mirid bugs in horticultural crops: Current challenges and future perspectives. Pest Manag Sci 77:33–42. <https://doi.org/10.1002/ps.6043>
- Ruberson JR, Nemoto H, Hirose Y (1998) Pesticides and conservation of natural enemies in pest management. In: Barbosa, P. (ed), Conservation Biological Control. Academic Press, San Diego, CA, pp. 207–220.

- Saito T, Takagi M, Tezuka T, Ogawara T, Wari D, (2021) Augmenting *Nesidiocoris tenuis* (Nesidiocoris) with a factitious diet of *Artemia* cysts to control *Bemisia tabaci* (Gennadius) on tomato plants under greenhouse conditions. *Insects* 12:265. <https://doi.org/10.3390/insects12030265>
- Sanchez JA (2008) Zoophytophagy in the plant bug *Nesidiocoris tenuis*. *Agric For Entomol* 10:75–80. <https://doi.org/10.1111/j.1461-9563.2007.00357.x>
- Sanchez JA, Lacasa A (2008) Impact of the zoophytophagous plant bug *Nesidiocoris tenuis* (Heteroptera: Miridae) on tomato yield. *J Econ Entomol* 101:1864–1870. <https://doi.org/10.1603/0022-0493-101.6.1864>
- Sanchez JA (2009) Density thresholds for *Nesidiocoris tenuis* (Heteroptera: Miridae) in tomato crops. *Biol Control* 51:493–498. <https://doi.org/10.1016/j.bioco ntrol.2009.09.006>
- Shimoda M, Honda K (2013) Insect reactions to light and its applications to pest management. *Appl Entomol Zool* 48:413–421. <https://doi.org/10.1007/s13355-013-0219-x>
- Shipp JL, Wang K (2006) Evaluation of *Dicyphus hesperus* (Heteroptera: Miridae) for biological control of *Frankliniella occidentalis* (Thysanoptera: Thripidae) on greenhouse tomato. *J Econ Entomol* 99:414–420 <https://doi.org/10.1603/0022-0493-99.2.414>.
- Trottin-Caudal Y, Millot P (1997) Etude de deux mirides en culture de tomate: *Macrolophus caliginosus* Wagner et *Nesidiocoris* (Cyrtopeltis) *tenuis* Reuter. *Infos Paris*, 131, 40–44.
- Trottin-Caudal Y, Fournier C, Leyre JM, Chabriere C (2006) La tomate sous serre dans le Sud-Est de la France. Protection contre la punaise *Nesidiocoris tenuis*. *Infos Ctifl*, 224, 30–35.
- Torres JB, Bueno AF (2018) Conservation biological control using selective insecticides – A valuable tool for IPM, *Biol Control* 126:53–64, <https://doi.org/10.1016/j.biocontrol.2018.07.012>.
- Uehara T, Ogino T, Nakano A, Tezuka T, Yamaguchi T, Kainoh Y, Shimoda M (2019) Violet light is the most effective wavelength for recruiting the predatory bug *Nesidiocoris tenuis*. *Biocontrol* 64:139–147. <https://doi.org/10.1007/s10526-019-09926-4>
- Urbaneja A, Montón H, Mollá O (2009) Suitability of the tomato borer *Tuta absoluta* as prey for *Macrolophus caliginosus* and *Nesidiocoris tenuis*. *J Appl Entomol* 133:292–296. <https://doi.org/10.1111/j.1439-0418.2008.01319.x>
- Wari D, Okada R, Takagi T, Yaguchi M, Kashima T, Ogawara T (2020) Augmentation and compatibility of *Beauveria bassiana* with pesticides against different growth stages of *Bemisia tabaci* (Gennadius); an in-vitro and field approach. *Pest Manag Sci* 76:3236-3252; <https://doi.org/10.1002/ps.5881>
- Wari D, Takagi M, Ogawara T (2021) Simplified insecticide toxicity determination method for *Nesidiocoris tenuis* using contaminated diet. *MethodsX*, 8:101220. <https://doi.org/10.1016/j.mex.2021.101220>.

## Tables

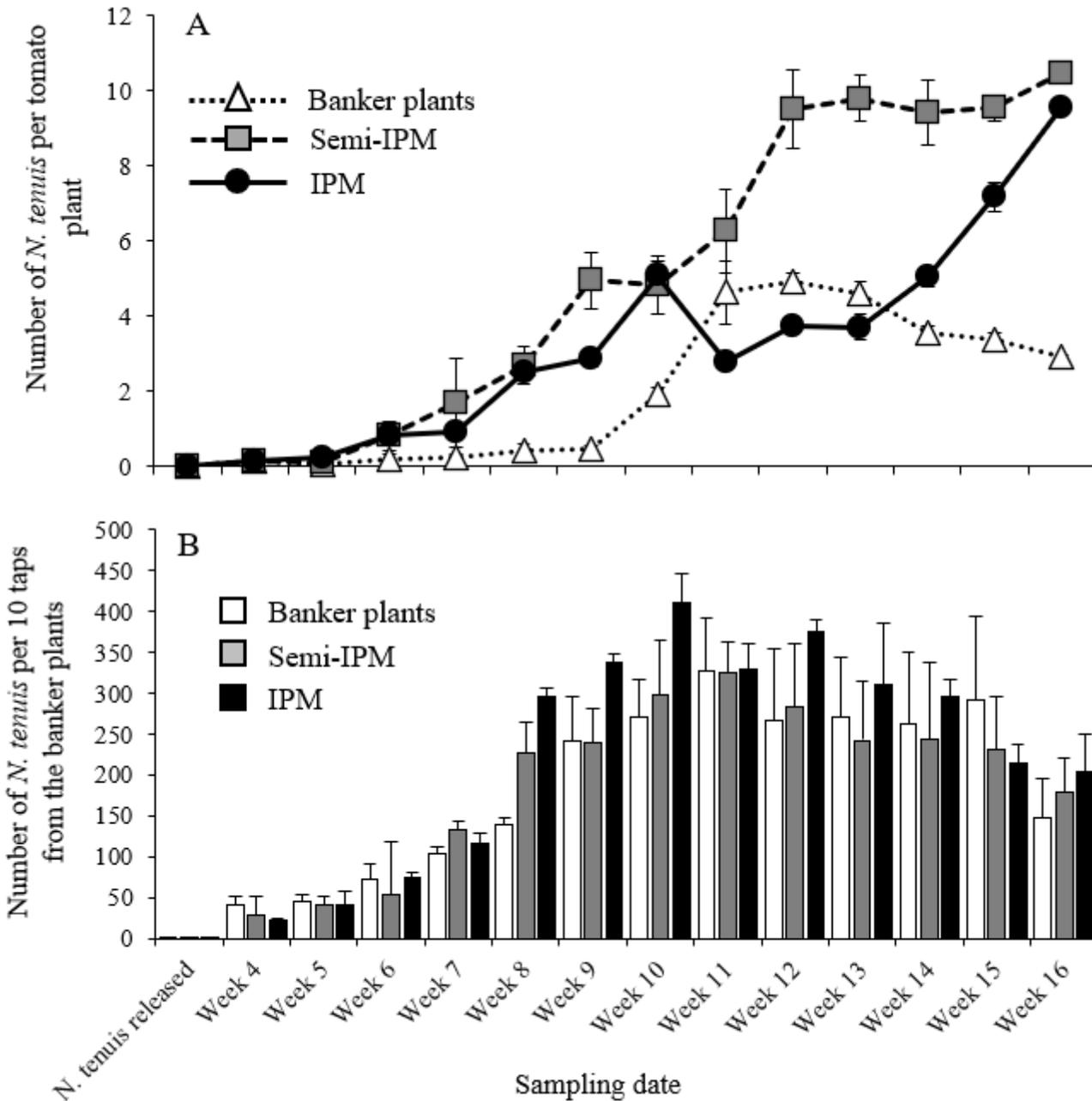
Tables 1-6 are available in the Supplementary Files.

## Figures



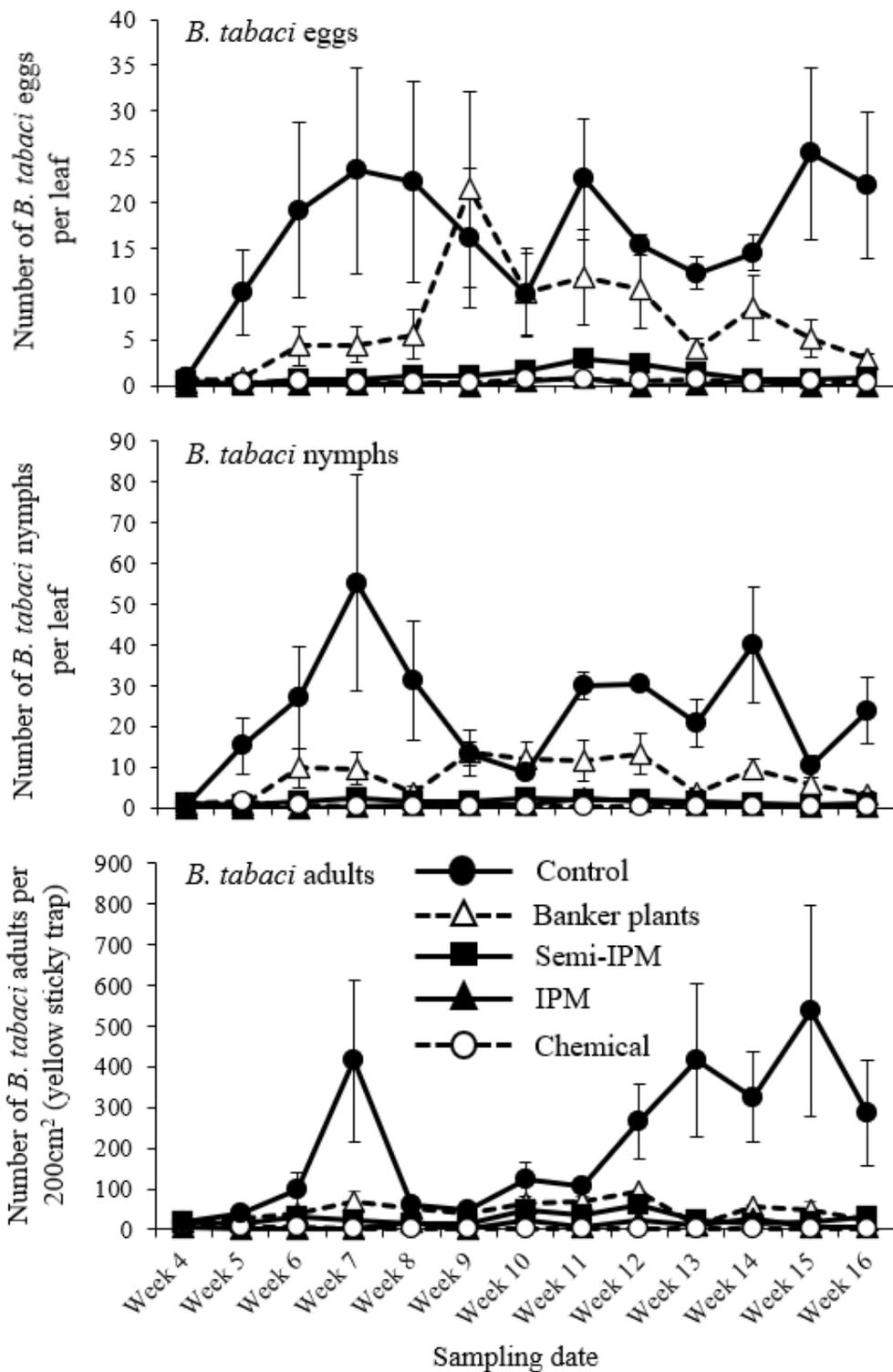
**Figure 1**

Schematic representation of the dynamics of *Nesidiocoris tenuis* movement from banker plants to tomato plants. (A) *N. tenuis* (inclusive of adults and nymphs) distribution on tomato plants in the four zones in banker plants only, Semi-IPM and IPM treatments, (B) schematic representation of the greenhouse layout of the three respective treatments. White bars represent the proportion of *N. tenuis* in zone 1, grey bars for zone 2, dark grey for zone 3, and black bars for zone 4. Banker plants were planted near zone 1 for all treatments while Violet-LEDs were set only in Semi-IPM and IPM treatments only on the opposite end of the greenhouse from the banker plants, adjacent to zone 4.



**Figure 2**

Mean ( $\pm$ SD) number of *Nesidiocoris tenuis* (inclusive of nymph and adults) on tomato plants (A) and banker plants (Verbena, Sesame and Cleome) (B) in banker plants, semi-IPM and IPM treatments.



**Figure 3**

Mean ( $\pm$ SD) number of *Bemisia tabaci* eggs, nymphs, and adults in the five treatments; Negative control, banker plants, semi-IPM, IPM and positive control treatment greenhouses.

## Supplementary Files

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- [WarietalSupplementarydata.pptx](#)
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