Thiacloprid + deltamethrin against the cotton aphid and the parasitoid wasp *Aphidius colemani*: From lethal to sublethal population effects

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**Abstract**
The side effects of insecticides on non-target species are important to secure the intended effectiveness of pest management programmes. The cotton aphid *Aphis gossypii* is a frequent problem in industrial greenhouse cultivation, and insecticide and parasitoids are often used for crop protection. Among insecticides, mixtures are playing increasing roles in pest management in the greenhouse production system, as well as parasitoid use. The insecticide mixture thiacloprid + deltamethrin and the parasitoid wasp *Aphidius colemani* are the main agents used against the cotton aphid and are the focus of this study. Here, we report the effects of the thiacloprid + deltamethrin on *A. gossypii* and *Ap. colemani*. The low concentrations 2.79 g a.i/L (LC\(_{10}\)) and 7.28 g a.i/L (LC\(_{30}\)) compromised the life parameters of the aphid progeny and increased the development time at all juvenile stages. In addition, fecundity, longevity and other parameters (\(r\), \(R_0\) and \(T\)) were significantly impaired by thiacloprid + deltamethrin at both concentrations. The median lethal time estimate (LT\(_{50}\)) for *Ap. colemani* was 18.73 h; the parasitoid mortality was significant up to 24 h after application but decreased afterward. Regardless, the parasitoid life table parameters were also compromised by insecticide exposure, similarly to the parasitoid population growth and parasitism efficacy. These results demonstrate the effect of the insecticide mixture against *A. gossypii*, and the increased risk of its adverse impacts on the parasitoid *Ap. colemani*, which signals against their simultaneous application to control this pest species.

**KEYWORDS**
cotton aphid, life-history, natural enemy, sublethal effect

**INTRODUCTION**

*Aphis gossypii* (Glover) (Hemiptera: Aphididae) is a cosmopolitan and polyphagous pest that attacks a large number of plant species around the world. This insect pest species can cause severe damage to its host through feeding and disease transmission (Hullé et al., 2020). The main management tactic used against *A. gossypii* (Glover) (Hemiptera: Aphididae) is the application of different chemical insecticide groups, including neonicotinoids, carbamate, pyrethroids and organophosphates (Wei et al., 2017). However, the chemical management is costly, provides only a temporary control and promotes the rapid development of resistance (Bengochea et al., 2012). The use of thiacloprid + deltamethrin against sucking and chewing pests takes advantage of the systemic activity of the former compound, a neonicotinoid, and the contact activity of the latter mixture component, the pyrethroid deltamethrin (Almasi et al., 2016). Despite their potential problems, insecticide mixtures combined with suitable biocontrol agents have great potential impact for pest management (Fontes et al., 2018; Momanyi et al., 2012; Van Driesche et al., 2008).
When insecticides are used in field crops, the insect population receives low concentrations and shows its effects because of several abiotic factors (Guedes et al., 2016). Physiological and behavioural effects of individuals that survived exposure to an insecticide at low concentration are described as sublethal effects (Desneux et al., 2007). However, many scientists believe that low concentrations may cause insect outbreaks in the field (Guedes et al., 2017; Guedes & Cutler, 2014; Zhang et al., 2019). Therefore, when examining the total impact of an insecticide, these multiple effects of low concentrations must be considered because they potentially compromise a range of behavioural and life-history traits of insect and mite species (Pires Paula et al., 2021; Qu et al., 2020; Desneux et al., 2005; Desneux, Wajnberg, et al., 2004). Insecticide resistance and the side effects of these compounds on non-target organisms are among the biggest concerns for pest management in agro-ecosystems (Desneux et al., 2007; Maroofpour et al., 2021; Ullah, Gul, Desneux, Gao, & Song, 2019). Since low concentrations last longer, their impacts can affect population dynamics, resulting in stress to communities and a potential risk to natural enemies’ ecological services (Desneux et al., 2007; Oliveira et al., 2019; Shah et al., 2020). A common (allegedly) cause of cotton aphid outbreaks is the absence of natural enemies, and, in some cases, the stimulation of aphid reproduction by pesticides (hormesis), which reinforces the above-stated concerns (Liang et al., 2021; Ullah, Gul, Desneux, Tariq, et al., 2019). The impact on biocontrol agents is particularly serious in contexts of frequent use, such as in greenhouse cultivation systems, where insecticide application is also important. Thus, their compatibility is a matter of interest for effective pest management (Glavan et al., 2020; López et al., 2017; Tappert et al., 2017).

The use of natural enemies is increasing in greenhouse pest management programmes due to their efficacy and applicability (Van Driesche et al., 2008). *Aphidius colemani* Viereck (Hymenoptera: Braconidae) is one of the parasitoids economically produced and globally distributed (Khatri et al., 2016, 2017; Sampaio et al., 2001). This parasitoid species is an important biological control agent, due to its mobility, high fecundity rate and short generation time, especially in industrial greenhouses. The performance of *Aphidius colemani* against aphid pest populations in greenhouses may reach efficacy levels as high as that of high-cost insecticides (Vásquez et al., 2006). In addition, the rearing of this parasitoid species is relatively easy, and the species is largely used against the cotton aphid (*Van Driesche et al., 2008; Vásquez et al., 2006*).

The combined use of biological control agents and insecticides requires awareness of the consequences of insecticides on the target insect, including natural enemies and pests (Blackman & Eastop, 2000; Peng et al., 2010). Nonetheless, the use of insecticide mixtures is increasing, which aggravates the concerns regarding their association to biocontrol agents in greenhouse pest management (Sandrock et al., 2014; Stark & Banks, 2003). The impact of such mixtures goes beyond their potentially lethal effects, as a range of sublethal effects frequently take place and are as important as or even more so than mortality. Life-table assessments are useful in that regard, as they encompass the impact of lethal and sublethal effects of insecticides (Chi et al., 2020). Meanwhile, traditional life tables deal only with the female population and ignore gender and stage differentiation and variable developmental rates among individuals, which are important issues in pest ecology. Therefore, research data should be collected and analysed in an integrated manner covering all life spans (all life stages) and both sexes. So, the two-sex life table theory was developed to consider the variable developmental rate and both sexes (Chi et al., 2020).

Even though the thiacloprid + deltamethrin combination is a novel foliar insecticide with broad-spectrum efficacy, less is known about its effects on pests and their enemies. Therefore, knowledge of the consequences of the effects of this insecticide on natural enemies and even the target pest can help integrated pest management programmes. The present study was carried out to assess the sublethal effects of thiacloprid + deltamethrin on the life-history and life table parameters of *A. gossypii* and *Ap. colemani*. However, the effect of insecticide mixture on parasitism rate is also evaluated to give an overview of the effect of insecticide on natural enemies.

**MATERIALS AND METHODS**

**Insecticide**

The insecticide mixture thiacloprid + deltamethrin (Proteus®) was obtained from Bayer Persian, Iran (Tehran). This insecticide mixture contains an oil dispersion with 10 g a.i/L of deltamethrin and 100 g a.i/L thiacloprid.

**Insects**

The cotton aphid colony was reared on cucumber (*Cucumis sativus* L. var. Emperator) under greenhouse conditions at 26 ± 2°C, relative humidity of 60%–70%, and 16:8 (L:D) photoperiod. *Aphis gossypii* population was collected from a greenhouse of Yasouj University. Every week, uninfected plants were replaced by aphid-infected plants.

*Aphidius colemani* was purchased from Gyah Co. (Karaj, Iran). They were maintained on cotton aphids with cotton wicks soaked in sugar water solution (10%) which were themselves maintained on cucumber plants in the same condition as an aphid colony. The plants were removed from cages when most aphids were mummified, and the mummified aphids were transferred into 1-L plastic jars covered with organdy cloth to allow aeration. The emerging adult parasitoids (24 h old) were collected with a manual aspirator.

**Aphid concentration-mortality bioassay**

Whereas *Ap. colemani* preferred to parasitize on *A. gossypii* immature (Barrette et al., 2009), the bioassay was performed on the third instar nymphs (<12 h old) of *A. gossypii* subjected to five insecticide mixture concentrations (2.75, 3.85, 13.75, 46.75, and 49.5 g a.i/L). In addition
to a (water containing 0.05% Tween-80 treated) control on plastic Petri (6 cm in diameter). Distilled water containing 0.05% Tween-80 was used to prepare the insecticide solutions. Cucumber leaf discs were placed on soaked cotton and then, 20 similar-aged third instar nymphs (<12 h old) were transferred to the discs using a soft brush. Next, 3 ml of either insecticide concentration were sprayed on aphids by Potter tower at 500 kPa pressure (Burkard Scientific, Uxbridge, UK). Mortality after 24 h was registered. The aphids were recorded as dead when unable to move after gently prodded with a hair brush. Three replicates were used for each of the six concentrations tested.

Diagnostic exposure time for the aphid parasitoid knockdown

These bioassays were investigated with 150 third instar nymphs (<12 h old) of the cotton aphid, using the highest low concentration (LC30) of the insecticide mixture previously established. The treated nymphs were subsequently transferred to plastic jars for parasitoid release. Ten female parasitoids were released into the jars, after 0, 12, 24, 48, 72 h of the aphid nymph exposure to the insecticide mixture. Parasitoid mortality was assessed every 24 h after their release, and the bioassays were replicated five times, always under the same environmental conditions used for the aphid bioassays.

Aphid life-table bioassay

In these life table experiments, the F1 generation nymphs obtained from the previously treated third instar nymphs (LC10 and LC30, besides the untreated control) were transferred to a new Petri containing cucumber leaf disks free from insecticide residues and maintained there until reaching the adult stage. Fifty similar-age newborn nymphs (<12 h old) from these adults were transferred on new leaf discs of cucumber over wet cotton in individual Petri dishes (6 cm diameter) with a soft brush. A hole (1.5 cm) was created at the center of each Petri dish cover to allow aeration, covered with an organza cloth. The individual Petri dishes were observed every 24 h, until the adult stage. The Petri dishes were maintained in the same condition as anaphid colony. Progeny production, mortality, and survival were recorded daily.

Parasitoid life table

Three concentrations of the insecticide mixture (LC10 and LC30, besides the control) obtained from the aphid bioassay were used to estimate the side effects of the mixture insecticide. For this purpose, 130 similar-age third-instar aphid nymphs were transferred to Petri dishes, as previously described, and subjected to insecticide spraying again, as already explained. The aphid nymphs that survived after 24 h exposure were placed in the plastic jars. Then, in order to parasitize the aphids, the parasitoid wasp was released into the jars and removed after 24 h. Then, the parasitized aphids were placed in each Petri dish and were daily monitored until mummified aphids appeared. The parasitoids that appeared were paired, and the survival and fecundity of each couple were recorded until the couple died. The third-instar aphid nymphs and a drop of honey were provided for the parasitoids during the observation period.

Concentration-mortality and survival analyses

The LC10, LC30 and LC50 values were determined based on probit analysis, using the SPSS software system (SPSS, 2011). The mortalities were corrected using Abbott’s formula (Abbott, 1925).

The time-mortality results of the parasitoid wasps using the LC30 estimated for the cotton aphid nymphs were subjected to Cox regression, with right-censored data and surviving time as independent variables (SPSS, 2011).

Life-table analyses

The life-table parameters of all individuals (aphids and parasitoids), including the age-stage specific survival rate (sxj) (where x = age in days and j = stage); the age-stage-specific fecundity (fXj) (parasitoid: daily number of eggs produced per female of age x; aphid: daily number of nymphs produced per female of age x); the age-specific survival rate (lx); the age specific fecundity (mx); the adult pre-oviposition period (APOP, parasitoid: the length of the pre-oviposition period beginning from adult emergence; aphid: the length of pre-reproductive period beginning from adult stage); the total pre-oviposition period (TPOP; parasitoid: the length of the pre-oviposition period beginning from birth; aphid: the length of pre-reproductive period beginning from birth); also, the population growth parameters, including the net reproductive rate (R0), intrinsic rate of increase (r) and mean generation time (T), were analysed by the computer program TWOSEX-MS Chart, based on the age–stage, two-sex life-table theory (Chi, 1988; Chi & Su, 2006; Tuan et al., 2014).

According to Chi & Liu (1985), age-specific survival rate was calculated as:

\[ l_x = \sum_{j=1}^{k} s_{xj} \]

where k is the number of stages. The age-specific fecundity (mx) was calculated as:

\[ m_x = \frac{\sum_{j=1}^{k} s_{xj} f_{xj}}{\sum_{j=1}^{k} s_{xj}} \]

Oviposition days (Od), the number of days in which females laid eggs for parasitoids or produced nymphs for aphids, was calculated as:
Od = \frac{\sum N_f D_x}{N_f}

where \(N_f\) is the number of female adults and \(D_x\) is the number of days that a female produced offspring (Chen et al., 2018).

The intrinsic rate of increase \((r)\) estimated by using iterative bisection method from the Euler-Lotka formula:

\[
\sum_{x=0}^{\infty} e^{-r(x+1)}lx = 1
\]

with age indexed from 0 (Goodman, 1982). The net reproduction rate is defined as the mean number of offspring that an individual can produce during its lifetime and was calculated as: \(R_0 = \sum_{x=0}^{\infty} lx\).

The mean generation time is the length of time a population needs to increase to \(R_0\)-fold of its size as the population reaches the stable age-stage distribution and was calculated as:

\[
T = \frac{\ln R_0}{r}
\]

The age-stage-specific life expectancy was calculated as:

\[
e_{xj} = \sum_{i=x}^{\infty} \sum_{y=j}^{\infty} s'_{iy}
\]

where \(s'_{iy}\) is the probability that an individual of age \(x\) and stage \(j\) will survive to age \(i\) and stage \(y\) (Chi, 1988; Chi & Su, 2006).

The age-stage reproductive value, which is the expected contribution of an individual of age \(x\) and stage \(j\) to the future population (Tuan et al., 2014) was calculated as:

\[
v_{xj} = \frac{e^{r(x+1)}}{s_{ij}} \sum_{i=y}^{\infty} \sum_{y=y}^{\infty} e^{-r(y+1)} \sum_{x}^{\infty} s'_{iy}
\]

The bootstrap technique with 100,000 bootstrap replicates was applied to calculate the standard errors of all population parameters, and the paired bootstrap test was used to compare differences at the 5% significance level (Chi et al., 2020).

Parasitism rate

The CONSUME-MS Chart was used to estimate daily parasitism rates (Chi, 2020; Chi & Yang, 2003). The following parameters were calculated: The age-specific parasitism rate \((k_x)\) is the mean number of aphids parasitized by Ap. colemani at age \(x\):

\[
k_x = \frac{\sum_{j=1}^{\beta} s_{ij} C_{ij}}{\sum_{j=1}^{\beta} s_{ij}}
\]

Taking the survival rate into consideration, the age-specific net parasitism rate \((q_x)\) was calculated as follows:

\[
q_x = k_x l_x
\]

The net parasitism rate \((C_0)\) is defined as the mean number of host parasitized by an average individual parasitoid during its entire life span and it was calculated as follows:

\[
C_0 = \sum_{x=0}^{\infty} k_x l_x = \sum_{x=0}^{\infty} \sum_{j=1}^{\beta} s_{ij} C_{ij}
\]

The transformation rate \((Q_p)\) is the number of prey aphid hosts needed for a parasitoid to produce a single offspring, and is calculated as:

\[
Q_p = \frac{C_0}{R_0}
\]

The stable parasitism rate \((\psi)\) as the total predation capacity of a population whose size is unity and at stable age-stage distribution. The stable parasitism rate and finite predation rate \((\omega)\) are calculated as follows equations:

\[
\psi = \sum_{x=0}^{\infty} \sum_{j=1}^{\beta} a_{ij} C_{ij}
\]

\[
\omega = \lambda \psi
\]

The bootstrap technique with 100,000 bootstrap replicates was applied to calculate the standard errors of all parameters, and the paired bootstrap test was used to compare differences at the 5% significance level.

RESULTS

Insecticide exposure and diagnostic exposure time

According to the results, the values 2.79, 7.28 and 14.1 g a.i/L were estimated for LC10, LC30 and LC50, respectively (Table 1).

Meanwhile, the median lethal time for 50% of the wasp population was 24 h (Figure 1). A quick decline in mortality was observed after such exposure time.

Insecticide effect on the aphid life-table

Thiacloprid + deltamethrin had a negative effect on the progeny development of treated third instar nymphs, which increased due to
TABLE 1  Toxicity of thiacloprid + deltamethrin on third instar nymphs of Aphis gossypii after 24 h

| Treatment                  | LC_{10} (g a.i/L) (95% CL) | LC_{20} (g a.i/L) (95% CL) | LC_{50} (g a.i/L) (95% CL) | Slope ± SE | \( \chi^2 \) (d.f.) | \( p \)-value |
|----------------------------|-----------------------------|-----------------------------|-----------------------------|------------|---------------------|-------------|
| Thiacloprid + deltamethrin | 2.79 (1.98–3.67)            | 7.28 (5.84–8.76)            | 14.1 (11.9–16.63)           | 1.92 ± 0.14 | 4.68 (3)            | 0.585       |

**FIGURE 1**  Survival of Aphidius colemani exposed to its host aphid LC_{30} of thiacloprid + deltamethrin

insecticide exposure (Table 2). Adult longevity also differs among the treatments (\( F = 1633.37; d.f. = 2; p < 0.001 \)). It is decreased by insecticide exposure, which was also observed for oviposition days (\( F = 3305.91; d.f. = 2; p < 0.001 \)) and fecundity (\( F = 5924.57; d.f. = 2; p < 0.001 \)) (Table 2).

The age-stage survival rate (\( s_{x} \)) of each aphid age-stage, at different insecticide concentrations, was plotted in Figure 2. It follows a concentration-dependent trend with the insecticide mixture, which significantly compromises survival through time. Results showed that the probability of newborn nymphs surviving to the adult stage declined when parental were exposed to both concentrations. Such negative trends exhibited similar tendency for the age-specific maternity (\( lxmx \)) and age-specific fecundity (\( vxj \)) (Figure 2). The progeny starting age was delayed under insecticide exposure, and the peak of fecundity was 9.8, 6.6 and 4.2 nymphs/female at the control, LC_{10} and LC_{30} respectively.

Moreover, both concentrations reduced the life expectancy (\( e_{x} \)) of all stages of aphid (Figure 3), with the highest decrease registered for the LC_{30} concentration. The age-stage-specific reproductive values (\( vxj \)) of A. gossypii females decreased when parental were exposed to both concentrations (Figure 3).

According to the results, the life-table parameters derived from the previous estimates for A. gossypii were also significantly affected (Table 3). The generation time increased (\( F = 14723.62; d.f. = 2; p < 0.001 \)) and net reproductive rate decreased (\( F = 5728.92; d.f. = 2; p < 0.001 \)) as insecticide concentrations increased, which consequently caused a sharp decrease in the intrinsic rate of population growth (\( r \)) (\( F = 19247.04; d.f. = 2; p < 0.001 \)) under insecticide mixture exposure.

**Life table of parasitoid wasp**

Based on the results, life table parameters of Ap. colemani were also significantly compromised by the insecticide mixture, following a concentration-dependent trend, including fecundity (\( F = 1146.94; d.f. = 2; p < 0.001 \)), development time (\( F = 2372.32; d.f. = 2; p < 0.001 \)) and longevity (\( F = 454.56; d.f. = 2; p < 0.001 \)) (Table 4). Similarly to that observed for the cotton aphid, the thiacloprid + deltamethrin also compromised the parasitoid age-specific maternity (\( lxmx \)), age-specific fecundity (\( vxj \)) and age-specific survival rate (\( sxj \)) (Figure 4). Results of the age-stage survival rate (\( s_{x} \)) of parasitoid showed that the probability of newborn larva surviving to the adult stage almost the same pattern as the control. The exposure of parasitoids to both concentrations resulted in a delayed and shorter period of oviposition compared to the control. Such trends were also similar to those for the parasitoid age-stage-specific reproductive values (\( vxj \)) and life expectancy (\( e_{x} \)) (Figure 5). The life expectancy (\( e_{x} \)) was reduced in all stages of LC_{30} treatment compared to control. The age-stage-specific reproductive values (\( vxj \)) of Ap. colemani females decreased due to LC_{30} concentration only, whereas LC_{10} concentration showed almost the same pattern as the control. These trends significantly impacted the demographic parameters obtained for the parasitoid wasp under exposure to the insecticide mixture (Table 5). Insecticide exposure compromised the mean generation time (\( F = 1698.19; d.f. = 2; p < 0.001 \)) and net reproductive rate (\( F = 132.70; d.f. = 2; p < 0.001 \)) by decreasing the former and increasing the latter, which reduced the intrinsic rate of population growth (\( r \)) (\( F = 442.95; d.f. = 2; p < 0.001 \)) (Table 5).

**Parasitism rate**

Table 5 presents the effect of the insecticide mixture at different concentrations on the parasitism rate of Ap. colemani. According to the result, a significant decrease was observed in the finite (\( k_{x} \)) (\( F = 91.82; d.f. = 2; p < 0.001 \)) and net parasitism rates (\( C_{x} \)) (\( F = 132.64; d.f. = 2; p < 0.001 \)). Figure 6 presents the effect of insecticide mixture at different concentrations on the age-specific net parasitism rate (\( q_{x} \)), age-specific parasitism rate (\( k_{x} \)) and parasitoid age-specific survival rate (\( l_{x} \)). Consequently, age-specific net parasitism rate (\( q_{x} \)) increased at first, but decreased as age increased. Also, both low concentrations reduced the age-specific parasitism rate (\( k_{x} \)) and age-specific net parasitism rate (\( q_{x} \)) of Ap. colemani.
TABLE 2  Life-history parameters (mean ± SE) of the progeny cotton aphid *Aphis gossypii*, untreated and treated with the LC$_{10}$ and LC$_{30}$ of thiacloprid + deltamethrin

| Parameters                        | Stage       | Control          | LC$_{10}$         | LC$_{30}$         |
|----------------------------------|-------------|------------------|-------------------|-------------------|
| Longevity of adult (days)        | Nymph 1     | 49               | 25.35 ± 0.67 a    | 19.21 ± 0.6 b     | 11.91 ± 0.61 c   |
| Longevity of preadult (days)     | Nymph 2     | 46               | 14.51 ± 0.38 a    | 6.16 ± 0.09 b     | 3.03 ± 0.17 c    |
| Longevity (days)                 | Nymph 3     | 50               | 29.34 ± 0.83 a    | 22.38 ± 1.18 b    | 17.32 ± 1.15 c   |
| Total preovipositional period*   | Nymph 4     | 49               | 13.18 ± 0.25 a    | 11.6 ± 0.36 b     | 6.68 ± 0.51 c    |
| Fecundity (offspring/adult)      |             | 49               | 80.24 ± 2.01 a    | 58.47 ± 2.4 b     | 25.88 ± 2.49 c   |

Note: SE were estimated by using the bootstrap technique with 100,000 resampling. Difference was compared by the paired bootstrap test (p < 0.05). Lower case letters indicate significant differences between the three concentrations.

*Nymph viviparous reproduction.

FIGURE 2  Age-stage survival rate ($s_{x}$), age specific survival rate ($l_{x}$), fecundity ($m_{x}$) and net maternity ($l_{x}m_{x}$) of the progeny cotton aphid *Aphis gossypii*, untreated and treated with LC$_{10}$ and LC$_{30}$ of thiacloprid + deltamethrin.
DISCUSSION

Pesticides are widely used in farms and degraded after application; hence, target and non-target insects are often exposed to low residues (Ali et al., 2017; Cutler, 2013; Guedes et al., 2016). The importance of such exposure is prevalent in the field and should not be neglected as it may affect the management of pest species (Ali et al., 2017; Xiao et al., 2015). An evaluation of the total impact on the insect population, specifically natural enemies, requires a thorough assessment of the entire life history of the insects (Müller, 2018). There may also be limitations to using current demographic approaches to estimate these effects of pesticides in laboratory settings due to the lack of monitoring crucial behaviours such as detecting parasitoids over long distances. Therefore, multistep bioassays provide a comprehensive way of assessing toxicity (Desneux et al., 2006).

FIGURE 3  Age-stage life expectancy ($e_{xy}$) and age-stage specific reproductive value ($v_{xy}$) of the progeny cotton aphid Aphis gossypii, untreated and treated with LC$_{10}$ and LC$_{30}$ of thiacloprid + deltamethrin

TABLE 3  Population parameters (mean ± SE) of the progeny cotton aphid Aphis gossypii, untreated and treated with the LC$_{10}$ and LC$_{30}$ of thiacloprid + deltamethrin

| Parameter                        | Control          | LC$_{10}$        | LC$_{30}$        |
|----------------------------------|------------------|------------------|------------------|
| Intrinsic rate of population growth ($r$) (day$^{-1}$) | 0.4647 ± 0.006 a | 0.3076 ± 0.007 b | 0.1670 ± 0.008 c |
| Net reproductive rate ($R_0$)    | 78.64 ± 2.50 a   | 50.28 ± 3.52 b   | 17.6 ± 2.38 c    |
| Generation time ($T$; days)      | 9.39 ± 0.11 a    | 12.73 ± 0.19 b   | 17.17 ± 0.32 c   |

Note: SE were estimated by using the bootstrap technique with 100,000 resampling. Difference was compared by the paired bootstrap test ($p < 0.05$). Lower case letters indicate significant differences between the three concentrations.
TABLE 4  Life-history parameters (mean ± SE) of the parasitoid wasp *Aphidius colemani*, developed on untreated or treated aphids with LC₁₀ and LC₃₀ of thiacloprid + deltamethrin

| Stage                                      | Treatment | Control  | LC₁₀     | LC₃₀      |
|--------------------------------------------|-----------|----------|----------|-----------|
| n                                          | Mean ± SE | n        | Mean ± SE | n         |
| Longevity of preadult stages (days)        | 49        | 13.55 ± 0.14 a | 47        | 14.53 ± 0.14 b | 46       | 15.39 ± 0.11 c |
| Longevity of male (days)                   | 22        | 17.91 ± 0.76 a | 20        | 16.85 ± 0.94 a | 16       | 12.88 ± 1.02 b |
| Longevity of female (days)                 | 27        | 19.81 ± 0.32 a | 27        | 18.07 ± 0.71 b | 30       | 14.2 ± 0.86 c  |
| Longevity (days)                           | 50        | 32.16 ± 0.50 a | 50        | 31.12 ± 0.75 a | 50       | 28.16 ± 0.8 b  |
| Adult preovipositional period (days)       | 27        | 0.48 ± 0.11 a  | 26        | 0.69 ± 0.11 a  | 27       | 1.56 ± 0.12 b  |
| Total preovipositional period (days)       | 27        | 14.22 ± 0.18 a | 26        | 15.46 ± 0.2 b  | 27       | 17.15 ± 0.19 c |
| Oviposition period (days)                  | 27        | 13.26 ± 0.41 a | 26        | 13.27 ± 0.4 a  | 27       | 9.56 ± 0.3 b   |
| Fecundity (no. eggs/female)                | 27        | 101.19 ± 2.58 a | 27        | 95 ± 4.28 a   | 30       | 58.43 ± 4.01 b |

Note: SE were estimated by using the bootstrap technique with 100,000 resampling. Difference was compared by the paired bootstrap test (*p* < 0.05). Lower case letters indicate significant differences between the three concentration.

FIGURE 4  Age-stage survival rate ($s_x$), age specific survival rate ($l_x$), fecundity ($m_x$), and net maternity ($l_xm_x$) of the parasitoid *Aphidius colemani*, developed on untreated or treated aphids with the aphid LC₁₀ and LC₃₀ of thiacloprid + deltamethrin.
The intent of the present work was to evaluate the effect of such low insecticide concentrations on a pest species, *A. gossypii*, and one of its important natural enemies, the parasitoid wasp *Aphidius colemani*. The results obtained indicated that both organisms are significantly compromised by the insecticide mixture, following a concentration-dependent trend.

Previous studies have demonstrated that, if the population growth of cotton sucking pests is controlled, natural enemies will be able to control the population of these species (Kerns & Stewart, 2000). However, our results dispute such a notion and are consistent with those of Majidpour et al. (2020), who reported that a low

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**FIGURE 5** Age-stage life expectancy ($e_{xy}$) and age-stage specific reproductive value ($v_{xy}$) of the parasitoid *Aphidius colemani*, developed on untreated or treated aphids with the aphid LC$_{10}$ and LC$_{30}$ of thiacloprid + deltamethrin

**TABLE 5** Population parameters and parasitism rate (mean ± SE) of the parasitoid wasp *Aphidius colemani*, developed on untreated or treated aphids with LC$_{10}$ and LC$_{30}$ of thiacloprid + deltamethrin

| Parameter                                      | Control            | LC$_{10}$          | LC$_{30}$          |
|------------------------------------------------|--------------------|--------------------|--------------------|
| Intrinsic rate of population growth ($r$) (day$^{-1}$) | 0.2081 ± 0.007 a   | 0.1929 ± 0.007 a   | 0.1643 ± 0.006 b   |
| Net reproductive rate ($R_0$)                  | 54.64 ± 7.24 a     | 51.3 ± 7.06 ab     | 35.06 ± 4.67 b     |
| Generation time (T; days)                      | 19.22 ± 0.21 a     | 20.41 ± 0.23 b     | 21.64 ± 0.16 c     |
| $C_0$ (hosts parasitoid$^{-1}$)                | 54.66 ± 7.23 a     | 51.30 ± 7.05 a     | 35.06 ± 4.66 b     |
| $Q_p$ (preys/offspring of predator)            | ≥1                 | ≥1                 | ≥1                 |
| $\psi$ (hosts parasitoid$^{-1}$)               | 0.33 ± 0.011 a     | 0.21 ± 0.009 a     | 0.18 ± 0.008 a     |
| $\omega$ (hosts parasitoid$^{-1}$ day$^{-1}$)  | 0.41 ± 0.006 a     | 0.25 ± 0.006 a     | 0.21 ± 0.007 a     |

Note: SE were estimated by using the bootstrap technique with 100,000 resampling. Difference was compared by the paired bootstrap test ($p < 0.05$). Lower case letters indicate significant differences between the three concentrations.
may reduce the population of natural enemies, which may favour the growth of A. gossypii population (Kidd et al., 1996). Mardani et al. (2016) found that thiacloprid + deltamethrin presented greater negative impact than pirimicarb and pymetrozine on Lysiphlebus fabarum (Marshall) (Hymenoptera: Aphididae) and reduced its survival, adult emergence and fecundity.

Thiacloprid + deltamethrin mixture was recognized as harmful due to its high toxicity to larval and adult stages of Hippodamia variegata (Goeze) (Coleoptera: Coccinellidae) and caused a severe reduction in all demographic parameters of this species (Almasi et al., 2016). Thiacloprid + deltamethrin also compromised the population parameters of L. fabarum, which is consistent with our findings for Ap. colemani. In another study, thiacloprid was tested on Trichogramma evanescens (Westwood) (Hymenoptera: Trichogrammatidae) and reduced adult emergence and parasitism by this species, although other species of this genus may not be as strongly affected (Abdulhay & Rathi, 2014). Bastos et al. (2006) investigated T. pretiosum (Riley) (Hymenoptera: Trichogrammatidae) and reported that thiacloprid did not affect adult emergence of this parasitoid. The difference in the results of these two studies with the present research may be due to differences in the parasitoid species, indicating that Ap. colemani is more susceptible than these two parasitoid species. Desneux, Pham-Delegue, and Kaiser (2004) also reported that the fecundity of A. ervi (Haliday) (Hymenoptera: Aphidiinae) at the low concentration (LD20) had significantly decreased by lambda-cyhalothrin. In another study, lambda-cyhalothrin at the lethal concentration (LD50) did not affect A. ervi responses to the odour from the aphid-infested plant Myzus persicae (Sulzer) (Homoptera: Aphididae) (Desneux, Rafalimanana, & Kaiser, 2004). Mead-Briggs (1992) found that the adult stages were significantly affected by thiacloprid, compared to the pre-imaginal stages in Ap. rhopalosiphi (DeStefani-Perez) (Hymenoptera: Braconidae). These findings suggest that Ap. colemani is more susceptible to the insecticide mixture thiacloprid + deltamethrin than other parasitoids.

The sublethal effects of insecticides on insect pests are an important consideration when selecting an insecticide. Based on previous research findings, outbreaks of cotton aphids have been attributed to the destruction of natural enemies and insecticide-mediated stimulation of aphid reproduction (Kerns & Stewart, 2000). Even at low concentrations, thiacloprid + deltamethrin presented a high potential to control A. gossypii. Given the results, thiacloprid + deltamethrin proved to be an effective insecticide for controlling A. gossypii, but the negative impact of insecticide mixture on life table parameters of Ap. colemani is a concern. Meanwhile, the decreased fecundity and longevity in the adult of cotton aphid may result from failure in the neurosecretory system under the influence of these insecticides. Thiacloprid + deltamethrin consists of a neonicotinoid and a pyrethroid, each with a different mode of action. Neonicotinoid insecticides affect acetylcholine receptors, while pyrethroids are sodium channel modulators, and both affect the insect nervous system. While affecting the nervous system, these compounds are also able to affect other physiological systems via indirect action, or via secondary action (Delpuech et al., 2001; Roubos et al., 2014; Vojoudi & Saber, 2013).
CONCLUSION

In summary, the insecticide mixture thiacloprid + deltamethrin is highly toxic to A. gossypii, and event at low levels significantly compromises all life table of this pest. Meanwhile, this insecticide imparted significant negative effects on Ap. colemani, indicating the unsuitability of its association with the biocontrol use of this aphid parasitoid against A. gossypii. Regardless, the present study’s findings suggest that thiacloprid + deltamethrin is effective against A. gossypii and provides adequate control. Although chemical control does not necessarily eradicate prey, allowing parasitoids to remain effective at low densities, the combined use of this pesticide with Ap. colemani is not suitable for pest management programmes. So, if the use of chemical control is necessary, thiacloprid + deltamethrin could be applied only when the damage is imminent.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

DATA AVAILABILITY STATEMENT

Due to its proprietary nature or ethical concerns, supporting data cannot be made openly available.

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