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Potential demographic impact of the insecticide mixture between thiacloprid and deltamethrin on the cotton aphid and two of its natural enemies

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Abstract

The use of pesticides impairs biological control in the agroecosystems and thus compromises the effectiveness of natural enemies against populations of pest species. The concerns over pesticides should expand beyond mortality and encompass their sublethal effects and their consequences to the target insect species and natural enemies to aid in our understanding of the potential and consequential use of these compounds. The present study aimed to determine the effects of an insecticide mixture on life-history and demographic parameters of the cotton aphid *Aphis gossypii* Glover (Hemiptera: Aphididae) and two of its main parasitoids – *Aphidius flaviventris* Kurdjumov (Hymenoptera: Aphelinidae) and *Aphidius colemani* Viereck (Hymenoptera: Braconidae). Based on the obtained results, thiacloprid + deltamethrin in its lethal concentration dose 20% of the pest population (LC_{20}) significantly affected the cotton aphid for two generations, increasing developmental time and demographic parameters. The LC_{20} manifested changes in many demographic parameters of the parasitoid *A. flaviventris*. This concentration also increased preadult and female longevity, total pre-ovipositional period, and mean generation time (T) of *A. colemani*, but no other demographic parameters were affected. Nonetheless, the insecticide mixture did not affect the parasitism rate of *A. colemani*. Thus, the thiacloprid + deltamethrin mixture significantly impaired the cotton aphid population and its parasitoid *A. flaviventris*. Therefore, the use of thiacloprid + deltamethrin is not encouraged for controlling the parasitoid *A. flaviventris*, but it is a relatively safe compound for *A. colemani*.

Introduction

Integrated pest management (IPM) uses biological, chemical, and agronomical techniques to control pest populations (Cocco *et al.*, 2020; Santoiemma *et al.*, 2020; Gugliuzzo *et al.*, 2021). Pesticides exhibit efficacy against target pests, but they can also have adverse effects on natural enemies (Desneux *et al.*, 2007; Biondi *et al.*, 2012, 2013; Guedes *et al.*, 2016). As biological control is very important for controlling pest populations, insecticide use should not compromise but rather complement biocontrol in reducing pest populations and reducing the risk of pest outbreaks (Fontes *et al.*, 2018). Thus, the potentially adverse effects of pesticides on natural enemies require investigation of their side effects in pest management programs (De Armas *et al.*, 2020; Rajaee *et al.*, 2022).

The cotton aphid *Aphis gossypii* Glover (Hemiptera: Aphididae) is an important cosmopolitan pest species with vegetables and ornamentals in open fields and greenhouses, and also in crop fields. This aphid species causes direct (e.g., aborted fruit) and indirect (e.g., transmitting viruses) damage to plants (Amini Jam *et al.*, 2014; Campolo *et al.*, 2014), and insecticide use is a major control method used against this species. As a result, this aphid species has developed resistance to the number of insecticides, and the use of insecticide mixtures is an important tactic to manage the problem (Herron *et al.*, 2001; Wang *et al.*, 2002). The thiacloprid + deltamethrin insecticide mixture controls sucking and chewing pests by systemic and contact exposure (Almasi *et al.*, 2016), which, when combined with biocontrol, has a high impact on the targeted pest species (Momanyi *et al.*, 2012; Fontes *et al.*, 2018). However, insecticide use to control a given species has potentially adverse effects on non-targeted organisms, such as parasitoids, predators, and pollinators (Desneux *et al.*, 2007; Souza *et al.*, 2020). Also, the outbreak of *A. gossypii* results from the reduction of natural enemy populations and, in some cases, may result from the stimulation of aphid reproduction by pesticides, a phenomenon known as insecticide-induced hormesis (Guedes and Cutler, 2014; Wang *et al.*, 2017; Ullah *et al.*, 2019; 2020).

Insect pest species such as aphids exhibit high reproductive rates, and their control frequently requires the use of selective insecticides along with natural enemies (Aparicio *et al.*, 2020; Hullé *et al.*, 2020; Maroofpour *et al.*, 2021). One of the most important approaches for the biological control of plant-feeding insects is the introduction of parasitoid wasps (Japoshvili and Abrantes, 2006). *Aphidius flaviventris* Kurdjumov (Hymenoptera: Aphelinidae) is known to prey on several aphid species in Iran (Abd-Rabou *et al.*, 2013). *Aphidius colemani* Viereck (Hymenoptera: Braconidae) is a solitary endoparasitoid used to biological control several economically important aphid pests. This parasitoid is one of the most successful biological control agents in greenhouses, and it has a worldwide distribution (Prado *et al.*, 2015; D'Ávila *et al.*, 2018). Compared to aphid parasitoids, *A. colemani* exhibits significant potential to spread and forage within greenhouses (Heinz, 1998).

Even though this insecticide mixture is a new foliar insecticide formulation with broad-spectrum efficacy for use in a wide range of crops, little information is currently available about the interaction of two natural enemies with insecticides, and particularly insecticide mixtures, including the effects of thiacloprid + deltamethrin on target pests and their natural enemies. This knowledge can help to establish more sustainable IPM programs. Majidpour *et al.* (2020) reported the effect of some sublethal concentrations (LC_{10} and LC_{30}) of thiacloprid + deltamethrin on *A. gossypii* and *A. flaviventris*. Based on that study, sublethal concentrations of the insecticide mixture reduced aphid longevity, fecundity, and life-table parameters in the first generation. Furthermore, the parasitoid's population growth and parasitism rate were significantly compromised at both concentrations under sublethal exposure (Majidpour *et al.*, 2020). Besides the short-term influences of insecticides, it is important to take into account the entire life-history as a comprehensive method for evaluating the total effect on insect population, including the impacts on the next generation, which have important implications for the success of an IPM program (Müller, 2018). Further and accurate assessments of these effects are important to acquire knowledge on the overall insecticide efficacy for long-term management of pest insect populations and their selectivity toward natural enemy species (Ferdenache *et al.*, 2019). Hence, this study has attempted to extend the previous research on concentration and insect tested about the sublethal effects of other concentrations on the successive generation. The present study was carried out to assess the effects of thiacloprid + deltamethrin on the life-history and demographic parameters of the cotton aphid *A. gossypii* and its parasitoids *A. flaviventris* and *A. colemani*. The impact of insecticide mixture on parasitism rate was also recorded to assess its effects on natural enemy efficacy under such exposure.

Materials and methods

Insect rearing

The cotton aphid colony was reared on cucumber plants (*Cucumis sativus* L. var. Emperator) (Cucurbitales: Cucurbitaceae). Cucumber seeds were planted in pots (18 cm in diameter and 19 cm high) without pesticide application at 26 ± 2°C, 60–70% relative humidity, and 16:8 (L:D) photoperiod. The original aphid colony was collected from Yasouj city in the Kohgiluyeh and Boyer-Ahmad Provinces of Iran, and these were transferred to a greenhouse at Yasouj University. Uninfested plants (with 5–7 true leaves) were provided every week to replace the aphid-infested plants in maintaining the insect colonies. In order to synchronize the age of the aphids, apterous female adults were placed on leaf disks and were allowed to lay eggs for 24 h. The nymphs were then transferred to new leaf disks and maintained for 3 days until they reached the 3rd nymphal stage.

A. flaviventris was obtained from mummified aphids of *A. gossypii* colonies and identified using morphological keys at the Iranian Research Institute of Plant Protection of Tabriz, Iran (Japoshvili and Abrantes, 2006). *A. 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 kept on cucumber plants. The plants were removed from the cages when most aphids were mummified, and the mummified aphids were transferred into 1-liter plastic jars.

Insecticide concentration-mortality bioassay

The insecticide mixture thiacloprid + deltamethrin (Proteus®) was obtained from Bayer Parsian, Iran. This insecticide mixture contains an oil dispersion with 10 g ai/l deltamethrin and 100 g ai/l thiacloprid.

To determine the toxicity of the thiacloprid + deltamethrin to *A. gossypii*, bioassays were performed on the 3rd instar nymphs. Stock solution and serial dilutions were prepared with distilled water added with Tween-80 as a surfactant at a concentration of 0.05%. Preliminary tests were conducted to assess the effective concentration range of the insecticide mixture. Five concentrations ranging from 3.3 to 52.25 g ai/l were subsequently established and used. The control treatment consisted of only distilled water and Tween-80. Each concentration was replicated three times. In Petri dishes (6 cm in diameter), leaf disks (5 cm diameter) of cucumber (*C. sativus* L.) were individually placed on soaked cotton, and 20 3rd instar nymphs (<12 h) were placed on each disk with a soft brush. Three milliliters of each insecticide mixture concentration were subsequently sprayed on the leaf disks containing aphids using a Potter tower (Burkard Scientific, Uxbridge, UK) at 5 bars of pressure. Mortality was recorded after 24 h of exposure. The aphids were recorded as dead when unable to move after being gently prodded with a hair brush.

Sublethal effects on the cotton aphid

Aiming to investigate life-history and demographic effects of the mixture thiacloprid + deltamethrin on *A. gossypii*, 3rd instar nymphs (<12 h old) were treated with a concentration corresponding to the LC_{20} (i.e., 4.88 g ai/l) of the insecticide mixture. This concentration is below the 30% mortality threshold usually recommended when focusing on sublethal effects of insecticides used in IPM programs (Desneux *et al.*, 2004). Ninety similar-aged 3rd instar nymphs were transferred to cucumber leaf disks placed on wet cotton in separate Petri dishes before spraying, as described above. In the control group, aphids were sprayed with distilled water and Tween-80. After 24 h of exposure, 50 surviving nymphs were individually transferred to new Petri dishes free from insecticide residues and kept under controlled conditions. Nymph survival was recorded every 24 h until reaching the adult stage. After adult emergence, survival, mortality, and the progeny of each adult female aphid were recorded daily.

Transgenerational sublethal effects in F1 generation of the cotton aphid

The F1-generation nymphs obtained from the insecticide-sprayed 3rd instar nymphs from the previous experiment were used in these experiments. The nymphs were transferred to new Petri

Table 1. Demographic parameters (mean ± SE) of the cotton aphid *A. gossypii* exposed to thiacloprid + deltamethrin at the LC_{20} = 4.88 g ai/l

		Treatment							
		F0				F1			
		n	Control	*n*	LC_{20}	*n*	Control	*n*	LC_{20}
Parameters	Stage		Mean ± SE		Mean ± SE		Mean ± SE		Mean ± SE
Development time (days)	1st instar	50	1.20 ± 0.06 a	50	1.24 ± 0.06 a	49	1.24 ± 0.06 a	46	2.93 ± 0.08 b
	2nd instar	49	1.18 ± 0.06 a	50	1.16 ± 0.05 a	49	1.14 ± 0.05 a	43	1.84 ± 0.07 b
	3rd instar	49	1.04 ± 0.03 a	45	2.68 ± 0.11 b	49	1.08 ± 0.03 a	41	1.51 ± 0.08 b
	4th instar	49	1.16 ± 0.03 a	35	1.8 ± 0.1 b	49	1.04 ± 0.02 a	40	1.93 ± 0.11 b
Longevity of adult (days)		49	27.53 ± 0.28 a	35	14.85 ± 0.48 b	49	25.34 ± 0.66 a	40	15.53 ± 0.7 b
Preadult (days)		49	4.59 ± 0.54 a	35	6.88 ± 0.10 b	49	4.51 ± 0.87 a	40	8.18 ± 0.13 b
Longevity (days)		50	31.52 ± 0.67 a	50	17.28 ± 1.06 b	50	29.34 ± 0.82 a	50	19.98 ± 1.2 b
Adult preovipositional period (days)		49	0.32 ± 0.10 a	35	2.71 ± 0.15 b	49	0.30 ± 0.65 a	39	2.1 ± 0.18 b
Total preovipositional period (days)		49	4.91 ± 0.13 a	35	9.6 ± 0.21 b	49	4.81 ± 0.10 a	39	10.26 ± 0.22 b
Oviposition period (days)		49	14.91 ± 0.53 a	35	8.57 ± 0.36 b	49	13.18 ± 0.24 a	39	7.54 ± 0.31 b
Fecundity (offspring/adult)		49	79.8 ± 3.07 a	35	37.02 ± 1.97 b	49	80.2 ± 1.99 a	40	41.23 ± 2.71 b

SEs were estimated by using the bootstrap technique with 100,000 resampling. Means were compared with the paired bootstrap test (P < 0.05). Lower case letters indicate significant differences between generations with control.

Table 2. Population parameters (mean ± SE) of the cotton aphid *A. gossypii* exposed to thiacloprid + deltamethrin at the LC_{20} = 4.88 g ai/l

	F0		F1	
Parameter	Control	LC_{20}	Control	LC_{20}
The intrinsic rate of increase (r_m; day^{-1})	0.445 ± 0.008 a	0.252 ± 0.010 b	0.464 ± 0.006 a	0.250 ± 0.008 b
Net reproductive rate (R_0; offspring/individual)	78.20 ± 3.39 a	25.92 ± 2.76 b	78.6 ± 2.51 a	32.98 ± 3.16 b
Generation time (T; days)	9.78 ± 0.18 a	12.89 ± 0.28 b	9.39 ± 0.11 a	13.98 ± 0.24 b

SEs were estimated by using the bootstrap technique with 100,000 resampling. Means were compared with the paired bootstrap test (P < 0.05). Lower case letters indicate significant differences between generations with control.

dishes without insecticide after 24 h. After adult emergence, 50 similar-aged newborn nymphs (1st instar) were transferred to cucumber leaf disks placed over wet cotton in separate Petri dishes. The subsequent experiments were carried out as described above.

Sublethal effects on aphid parasitoids

In order to estimate the effect of the insecticide mixture thiacloprid + deltamethrin on the aphid parasitoids *A. flaviventris* and *A. colemani*, we used the LC_{20} obtained from the concentration-mortality bioassay with the cotton aphid *A. gossypii*. For this purpose, 130 similar-aged 3rd instar nymphs of *A. gossypii* were placed on the Petri dish, as previously described. Then, the aphid nymphs were treated with LC_{20} of the insecticide mixture using a Potter spray tower, as previously described. The control group consisted of aphids sprayed with distilled water and Tween-80. One-liter plastic jars were used to transfer the surviving nymphs after 24 h. Then, the adult parasitoids (male and female) were released into the jars, and the parasitism on treated and untreated aphids remained for 24 h before removing the adult parasitoids. Each aphid exposed to *A. flaviventris* and *A. colemani* parasitism was transferred to a separate Petri dish. The appearance of mummified aphids was monitored daily. After the emergence of adult parasitoids, the females and males were paired (32 and 26 pairs for *A. flaviventris* and *A. colemani*, respectively) and daily provided with 20 aphid nymphs (3rd instar) and honey. After 24 h, the parasitoids were removed, and the Petri dishes were kept until mummified aphids emerged. The fecundity and longevity of each wasp couple were recorded daily until the couple died. The treatments were maintained under the same environmental conditions previously described.

Statistical analyses

The concentration-mortality values were subjected by probit analysis using SPSS software (SPSS, 2011). The mortalities were subjected to Abbott's formula to correct the natural mortality observed in control (Abbott, 1925).

The life-table parameters for both aphids and parasitoids, such as development time of different stages, fecundity, longevity, and population parameters, were analyzed by the computer program TWOSEX-MS Chart, based on the age-stage, two-sex life-table

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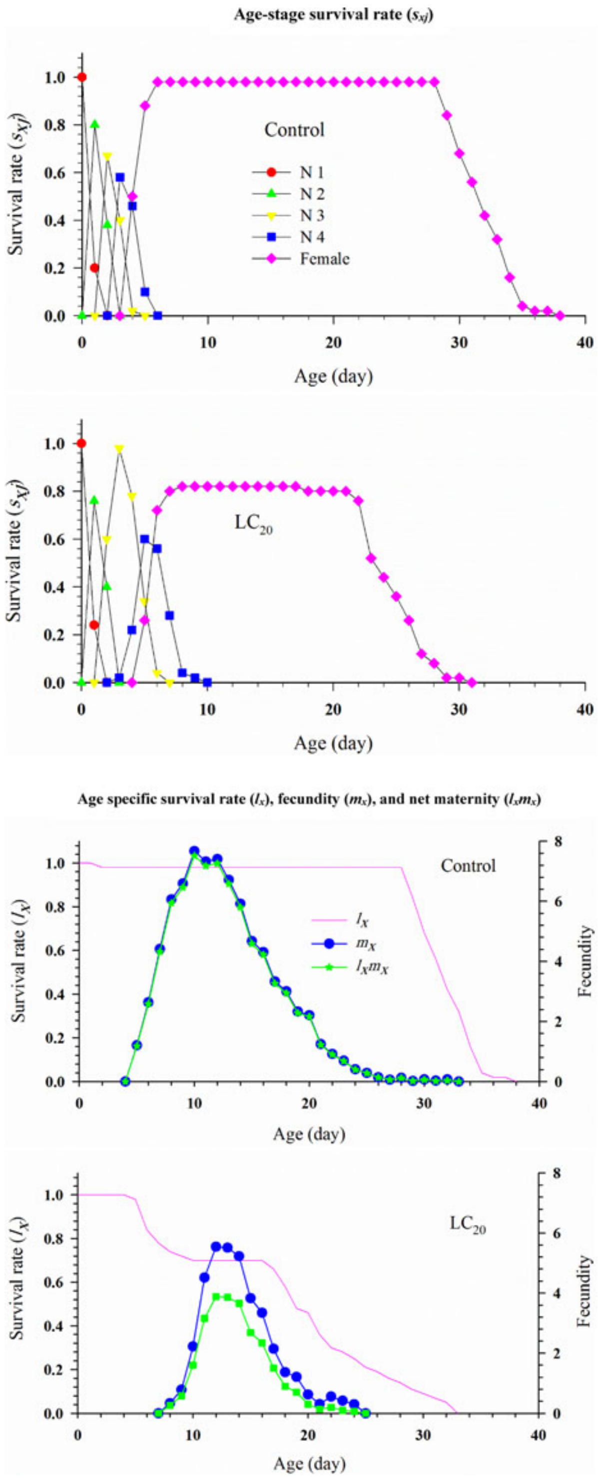

Figure 1. Age-stage survival rate (s_{xj}) and age-specific survival rate (l_x), fecundity (m_x), and net maternity (l_xm_x) of F0 generation of *A. gossypii* exposed to thiacloprid + deltamethrin at the LC_{20} = 4.88 g ai/l.

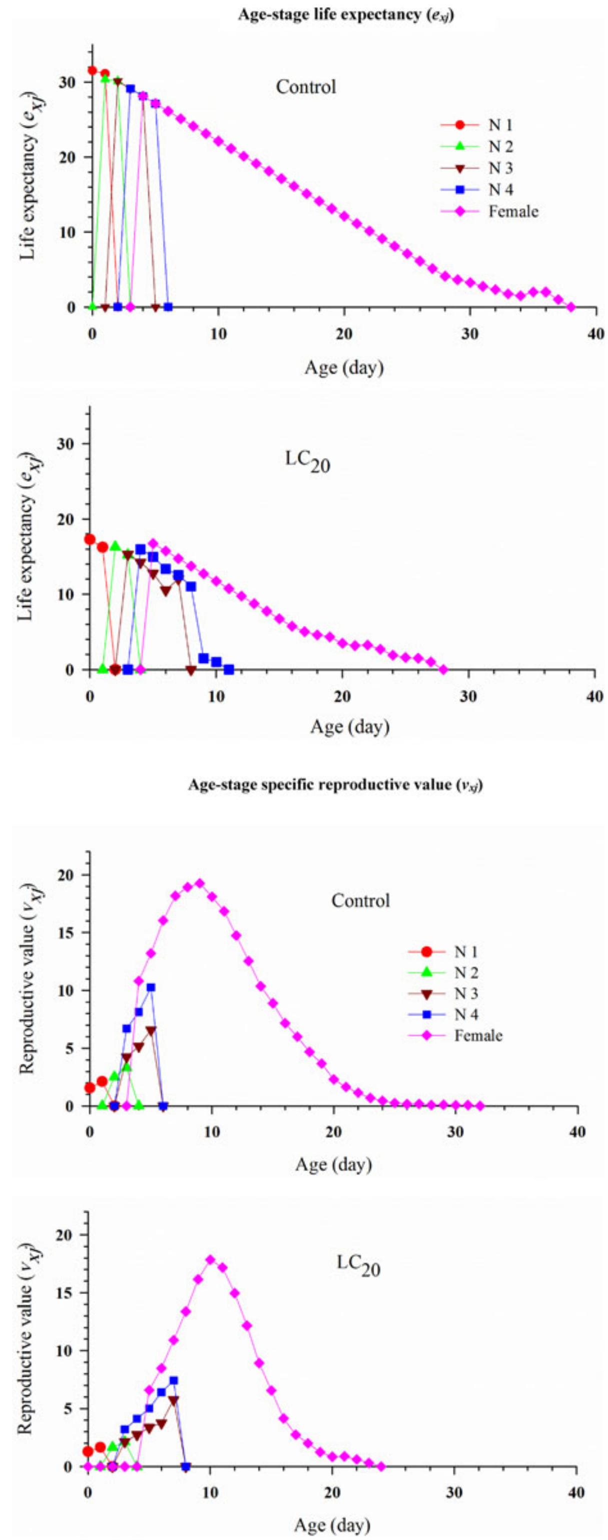

Figure 2. Age-stage life expectancy (e_{xj}) and age-stage specific reproductive value (v_{xj}) of F0 generation of *A. gossypii* exposed to thiacloprid + deltamethrin at the LC_{20} = 4.88 g ai/l.

theory (Chi, 1988; Chi and Su 2006; Tuan *et al.*, 2014; Chi *et al.*, 2020). The bootstrap technique with 100,000 bootstrap replicates was applied to calculate the standard errors of all population parameters (Chi, 2020b).

The CONSUME-MS Chart was used to estimate daily parasitism rates (Chi and Yang, 2003; Chi 2020a). The parameters calculated were: age-specific net parasitism rate (q_x), net parasitism rate (C_0), finite predation rate (ω), stable parasitism rate (ψ), age-specific parasitism rate (k_x), and transformation rate (Q_p). The bootstrap technique with 100,000 bootstrap replicates was applied to calculate the standard errors of all parameters.

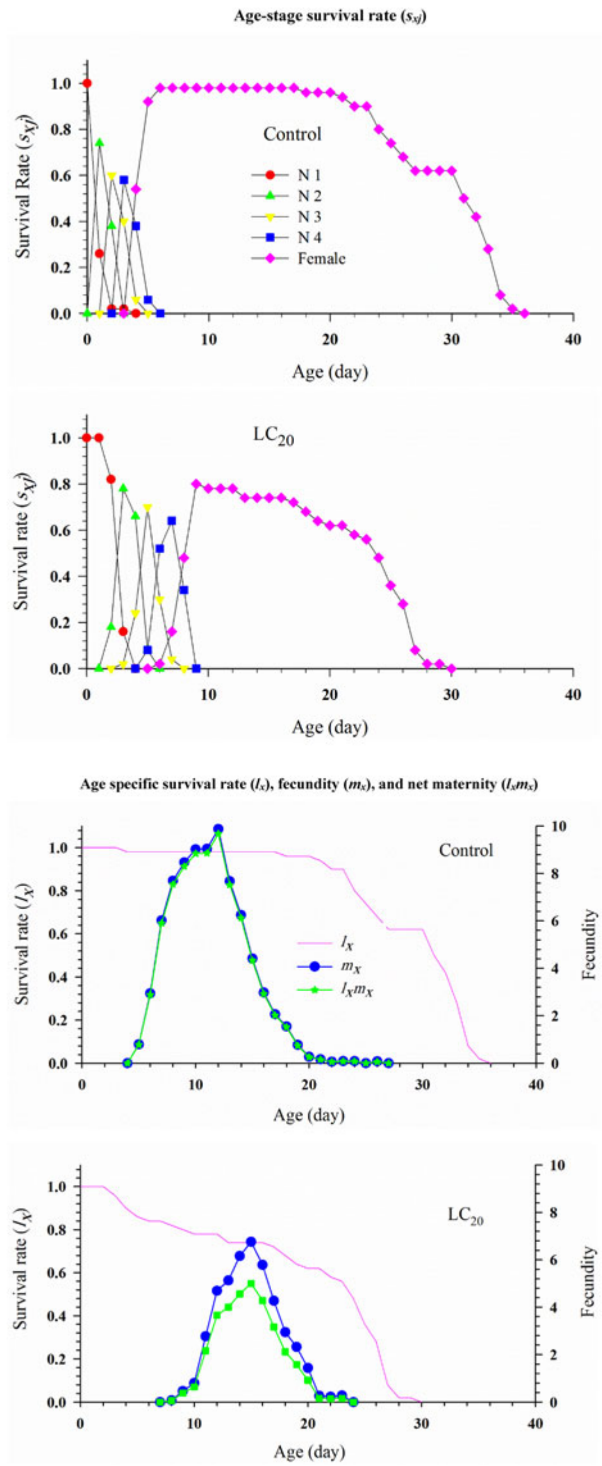

Figure 3. Age-stage survival rate (s_{xj}) and age-specific survival rate (l_x), fecundity (m_x), and net maternity (l_xm_x) of F1 generation of *A. gossypii* exposed to thiacloprid + deltamethrin at the LC_{20} = 4.88 g ai/l.

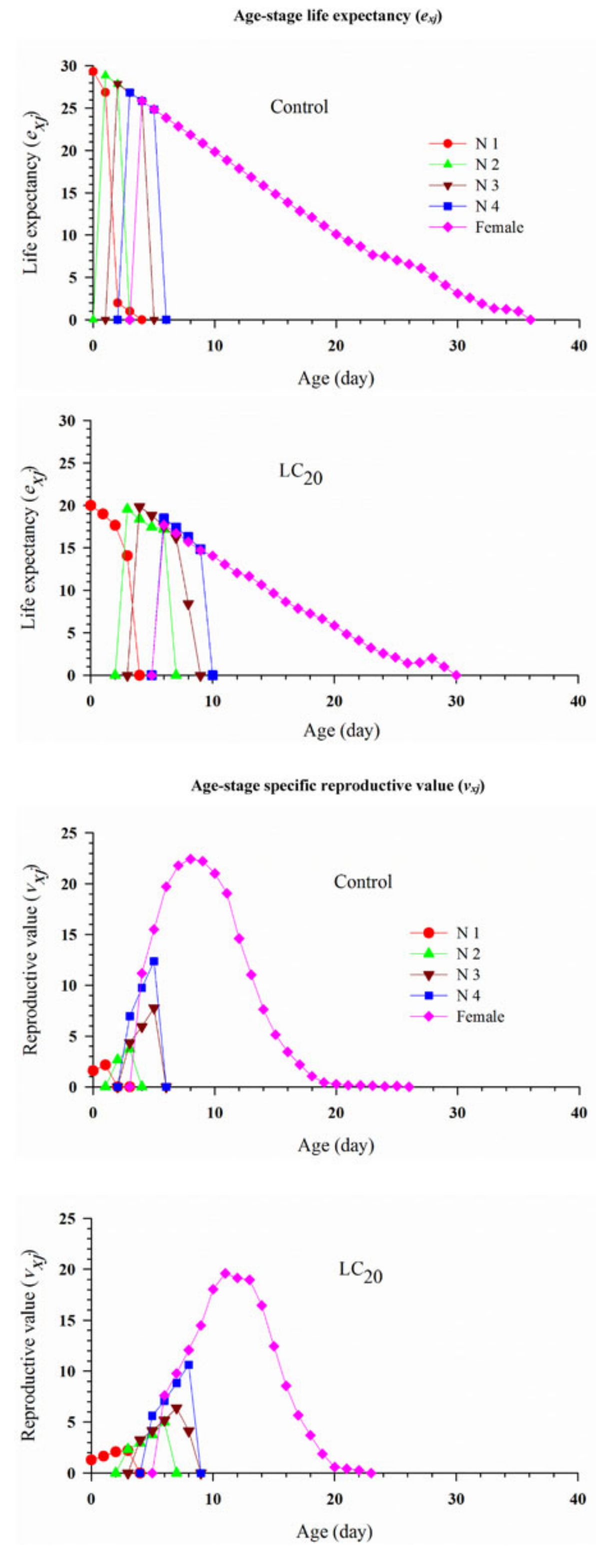

Figure 4. Age-stage life expectancy (e_{xj}) and age-stage specific reproductive value (v_{xj}) of F1 generation of *A. gossypii* exposed to thiacloprid + deltamethrin at the LC_{20} = 4.88 g ai/l.

Results

Concentration-mortality bioassays

The probit model was suitable for describing the concentration-mortality trend obtained with the aphids when exposed to the insecticide mixture in the concentration-mortality bioassay. The LC_{20} and LC_{50} values for the mixture thiacloprid + deltamethrin against *A. gossypii* were 4.88 and 14.1 g ai/L, respectively (Supplementary table 1).

Table 3. Demographic parameters (mean ± SE) of the parasitoid *A. flaviventris* exposed to thiacloprid + deltamethrin at the LC_{20} = 4.88 g ai/l

	Treatment			
	n	Control	*n*	LC_{20}
Stage		Mean ± SE		Mean ± SE
Preadult (days)	48	13.97 ± 0.11 a	44	15.99 ± 0.1 b
Longevity of male (days)	20	17.30 ± 0.91 a	12	9.5 ± 1.41 b
Longevity of female (days)	28	18.53 ± 0.70 a	32	11.37 ± 0.79 b
Longevity (days)	50	31.32 ± 0.70 a	50	25.68 ± 0.79 b
Adult preovipositional period (days)	27	0.37 ± 0.09 a	27	1.88 ± 0.14 b
Total preovipositional period (days)	27	14.55 ± 0.16 a	27	18.11 ± 0.18 b
Oviposition period (days)	27	13.66 ± 0.39 a	27	8.55 ± 0.23 b
Fecundity (offspring/adult)	28	97.10 ± 4.25 a	32	48.53 ± 3.99 b

SEs were estimated by using the bootstrap technique with 100,000 resampling. Means were compared with the paired bootstrap test ($P < 0.05$). Lower case letters indicate significant differences between the two treatments.

Sublethal impacts on the cotton aphid

According to the results, the insecticide mixture causes significant impacts on various developmental and biological parameters at different stages of the cotton aphid *A. gossypii* (table 1). Starting from the 3rd instar, the developmental time extended following exposure to the mixture thiacloprid + deltamethrin compared with the control leading to an increase of the preadult period. Total pre-ovipositional and adult pre-ovipositional periods were also significantly higher. At the same time, a significant decrease was observed in the adult developmental time, fecundity, oviposition period, and longevity of the insecticide-exposed aphids. Furthermore, the insecticide mixture affected the aphid population parameters (table 2), causing significant increase in the mean generation time (T) ($F = 4114.29$; $df = 1$; $P < 0.001$), and decreasing the net reproductive rate (R_0) ($F = 7101.66$; $df = 1$; $P < 0.001$) and intrinsic rate of increase (r) ($F =$ 10,487.69; $df = 1$; $P < 0.001$).

The exposure to thiacloprid + deltamethrin also had detrimental impacts on the age-stage survival rate (s_{xj}) of each age-stage, the age-specific survival rate (l_x), the age-specific fecundity (m_x) and maternity ($l_x m_x$), the life expectancy (e_{xj}), and also the age-stage-specific reproductive values (v_{xj}) of the aphid *A. gossypii* (figs 1 and 2).

Significant overlap among life stages was observed in untreated aphids due to the variable developmental rate among individuals but was not as evident as in the insecticide-exposed aphids. In these aphids, not only was the probability that a newborn nymph surviving until the adult stage lower (fig. 1), but the start of egg-laying was also delayed (fig. 1), the age-specific fecundity was reduced, and their life expectancy decreased as age increased (fig. 2).

Transgenerational sublethal impacts on the cotton aphid

Thiacloprid + deltamethrin impacted the F1 generation of the cotton aphid (tables 1 and 2). The developmental time significantly increased in all instars and preadult stages of *A. gossypii* exposed to the insecticide mixture (table 1). Significant increase was observed in the adult preovipositional period ($F = 4355.02$; $df = 1$; $P < 0.001$) and total preovipositional period ($F = 2389.81$; $df = 1$; $P < 0.001$) compared to the control. At the same time, the insecticide significantly reduced oviposition ($F = 9201.13$; $df = 1$; $P < 0.001$) and fecundity ($F = 6262.28$; $df = 1$; $P < 0.001$) compared to the control group. All population parameters were significantly reduced after insecticide exposure (table 2).

Table 4. Population parameters and parasitism rate (mean ± SE) of the parasitoid *A. flaviventris* exposed to thiacloprid + deltamethrin at the LC_{20} = 4.88 g ai/l

Parameter	Control	LC_{20}
The intrinsic rate of increase (r_m; day^{-1})	0.204 ± 0.007 a	0.155 ± 0.006 b
Net reproductive rate (R_0; offspring/individual)	54.38 ± 7.19 a	31.06 ± 4.13 b
Generation time (T; days)	19.49 ± 0.23 b	22.03 ± 0.18 a
C_0 (hosts parasitoid^{-1})	54.38 ± 7.19 a	31.06 ± 4.13 b
Q_p (preys/offspring of predator)	≅1	≅1
ψ (hosts parasitoid^{-1})	0.23 ± 0.08 a	0.17 ± 0.01 b
ω (hosts parasitoid^{-1} day^{-1})	0.28 ± 0.001 a	0.20 ± 0.001 b

SEs were estimated by using the bootstrap technique with 100,000 resampling. Means were compared with the paired bootstrap test ($P < 0.05$). Lower case letters indicate significant differences between the two treatments.

The overlap among life stages in the F1 generation decreased, and the start of egg-laying was delayed by insecticide exposure (fig. 3). Furthermore, the insecticide mixture reduced the life expectancy (e_{xj}) of all stages and the age-stage-specific reproductive value (v_{xj}) (fig. 4).

Sublethal impacts on the parasitoid A. flaviventris

The results of demographic parameters of *A. flaviventris* indicated that the insecticide mixture had also effects on the different stages and population parameters of this parasitoid when reared on exposed host (tables 3 and 4). In fact, significant decreases were registered in the longevity of male ($F = 390.55$; $df = 1$; $P < 0.001$) and female ($F = 1373.22$; $df = 1$; $P < 0.001$) parasitoids, oviposition period ($F = 3877.81$; $df = 1$; $P < 0.001$) and total fecundity ($F = 2113.04$; $df = 1$; $P < 0.001$), while the adult pre-ovipositional period ($F = 2127.47$; $df = 1$; $P < 0.001$) and total pre-ovipositional period ($F = 5635.39$; $df = 1$; $P < 0.001$) were extended under

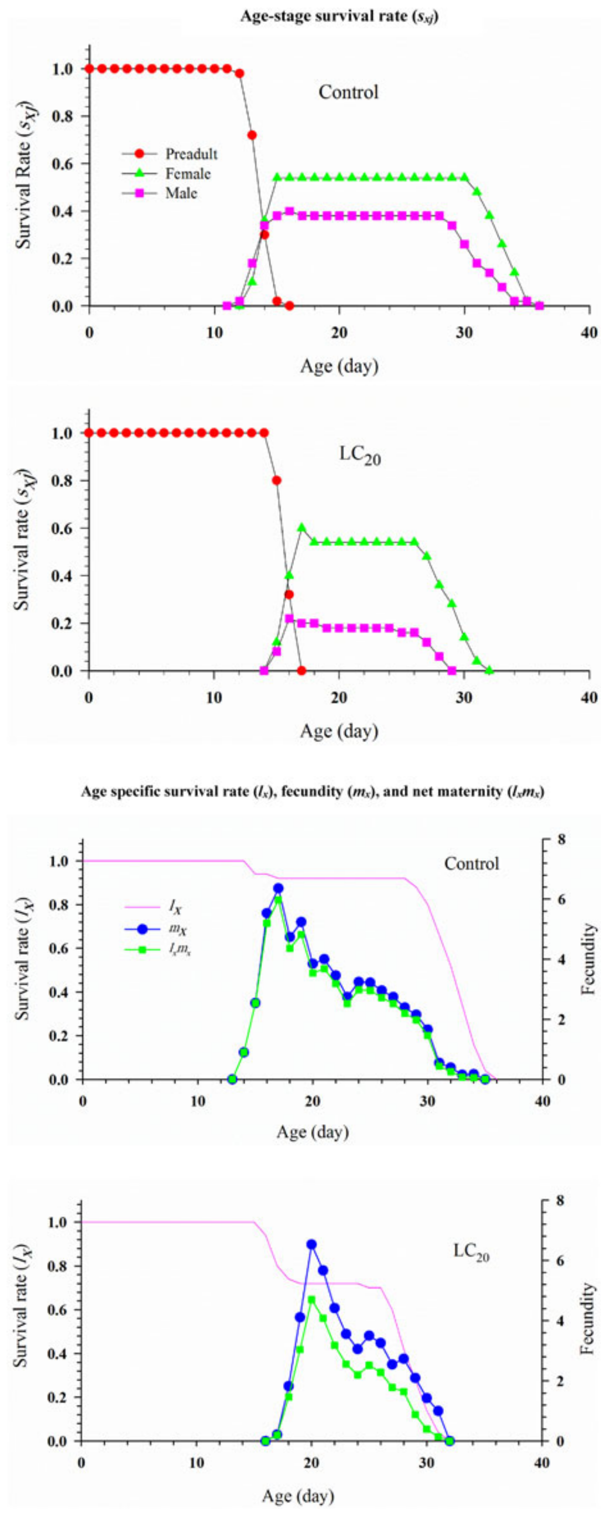

Figure 5. Age-stage survival rate (s_{xj}) and age-specific survival rate (l_x), fecundity (m_x), and net maternity ($l_x m_x$) of *A. flaviventris* exposed to thiacloprid + deltamethrin at the LC_{20} = 4.88 g ai/l.

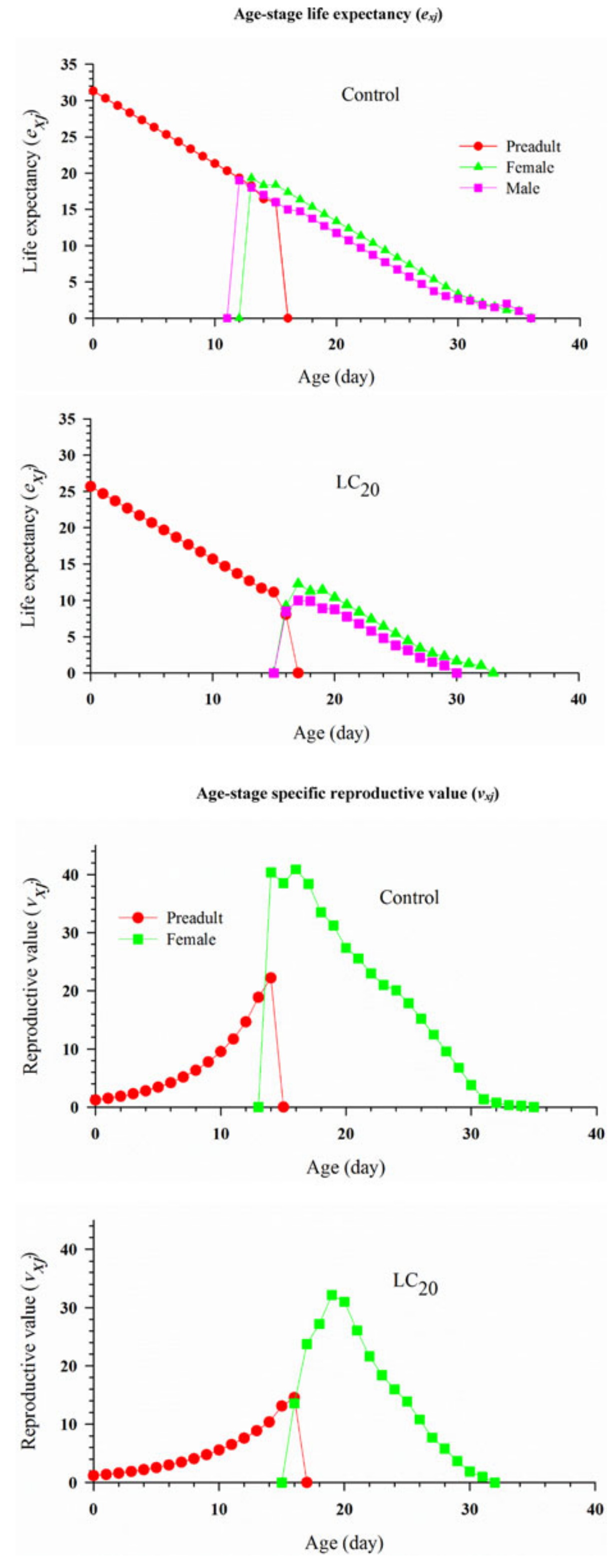

Figure 6. Age-stage life expectancy (e_{xj}) and age-stage specific reproductive value (v_{xj}) of *A. flaviventris* exposed to thiacloprid + deltamethrin at the LC_{20} = 4.88 g ai/l.

insecticide exposure. Moreover, the intrinsic rate of increase (r_m) ($F = 1162.77$; $df = 1$; $P < 0.001$), and net reproductive rate (R_0) ($F = 395.69$; $df = 1$; $P < 0.001$) of the parasitoid *A. flaviventris* exhibited a significant decrease compared with unexposed parasitoids, while their mean generation time (T) ($F = 4454.46$; $df = 1$; $P < 0.001$) significantly increased (table 4). Finally, the start of egg-laying was delayed (fig. 5), the life expectancy reduced (fig. 6), and the age-specific fecundity and age-stage-specific reproductive value decreased with the insecticide mixture (fig. 6).

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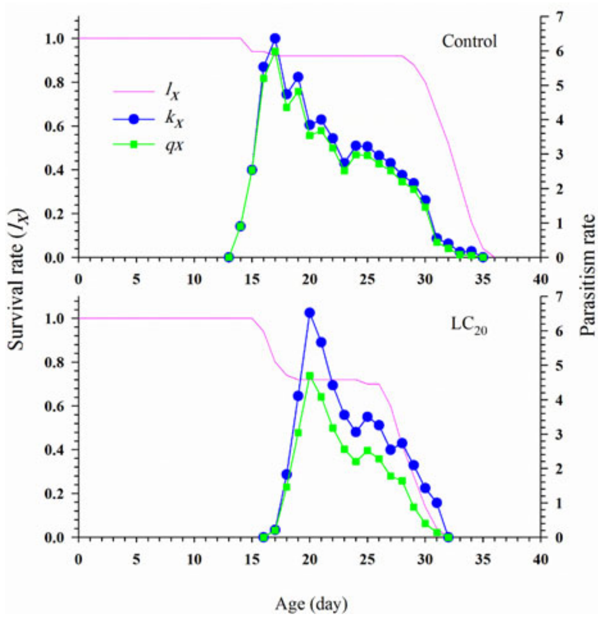

Figure 7. Age-specific survival rate (l_x), age-specific host feeding rate (k_x), and age-specific net host feeding rate (q_x) of *A. flaviventris* exposed to thiacloprid + deltamethrin at the LC_{20} = 4.88 g ai/l.

The finite predation rate (ω) and net parasitism rate (C_0) significantly decreased under insecticide exposure (table 4). The transformation rate (Q_p) indicates that *A. flaviventris* required almost one aphid to produce a single parasitoid egg. Also, the age-specific net parasitism rate (q_x) increased at first and then decreased as age increased. The start of parasitism was delayed under insecticide exposure (fig. 7). Based on these results, the insecticide mixture reduced the age-specific net parasitism rate (q_x) (fig. 7).

Sublethal effects on the parasitoid A. colemani

Thiacloprid + deltamethrin affected *A. colemani* life-history parameters. The length of the preadult period (F = 670.19; df = 1; P < 0.001), female longevity (F = 357.84; df = 1; P < 0.001), and total preovipositional period (F = 417.05; df = 1; P < 0.001) were affected by the LC_{20}, showing a significant increase when compared to the control, but no significant difference was observed in other life-history traits (table 5). Furthermore, among the life-table parameters of *A. colemani*, only mean generation time (T) (F = 394.61; df = 1; P = 0.055) was significantly different from the control group (table 6).

The exposure to thiacloprid + deltamethrin had no detrimental impacts on the age-stage survival rate (s_{xj}) of each age-stage and the age-specific survival rate (l_x) of this parasitoid. Furthermore, the age-specific fecundity (m_x) and maternity ($l_x m_x$), the life expectancy (e_{xj}), and age-stage-specific reproductive values (v_{xj}) of this parasitoid were also not affected by exposure to the insecticide mixture (figs 8 and 9).

The parasitism rate of *A. colemani* at different concentrations is shown in table 6. According to the result, the insecticide mixture caused a decrease in the net parasitism rate (C_0) and finite predation rate (ω). The results of age-specific survival rate (l_x), the age-specific parasitism rate (k_x), and the age-specific net parasitism rate (q_x) are presented in fig. 10. Q_p shows that *A. colemani* required almost one aphid to produce a single parasitoid egg. The age-specific net parasitism rate (q_x) increases first and then decreases as age increases. Based on these results, the LC_{20} reduced the age-specific parasitism rate (k_x) and age-specific net parasitism rate (q_x) of *A. colemani*. The start of parasitism was also delayed under insecticide exposure.

Discussion

Thiacloprid + deltamethrin showed different effects on the target pest and its natural enemy. According to the present study results, thiacloprid + deltamethrin exhibits high toxicity to *A. gossypii* and negatively impacts the demographic parameters of this pest species. Effects of thiacloprid + deltamethrin negatively affected demographic parameters in successive generations of the cotton aphid (Kerns and Stewart, 2000).

Shi *et al.* (2011) reported that fecundity and longevity of *A. gossypii* at LC_{20} were significantly reduced by thiacloprid. Our results are also consistent with Majidpour *et al.* (2020), reporting that low concentrations (LC_{10} and LC_{30}) of thiacloprid + deltamethrin compromise the demographic parameters of *A. gossypii*

Table 5. Demographic parameters (mean ± SE) of the parasitoid *A. colemani* exposed to thiacloprid + deltamethrin at the LC_{20} = 4.88 g ai/l

	Treatment			
	n	Control	*n*	LC_{20}
Parameters		Mean ± SE		Mean ± SE
Preadult (days)	49	13.55 ± 0.14 b	48	14.33 ± 0.16 a
Longevity of male (days)	22	17.91 ± 0.76 a	22	16.18 ± 0.95 a
Longevity of female (days)	27	19.81 ± 0.32 a	26	18.19 ± 0.31 b
Longevity (days)	50	32.16 ± 0.49 a	50	30.94 ± 0.65 a
Adult preovipositional period (days)	27	0.48 ± 0.11 a	26	0.77 ± 0.10 a
Total preovipositional period (days)	27	14.22 ± 0.18 b	26	15.38 ± 0.24 a
Oviposition period (days)	27	13.26 ± 0.41 a	26	12.69 ± 0.41 a
Fecundity (offspring/adult)	27	101.19 ± 2.58 a	26	96.88 ± 2.44 a

SEs were estimated by using the bootstrap technique with 100,000 resampling. Means were compared with the paired bootstrap test (P < 0.05). Lower case letters indicate significant differences between the two treatments.

Table 6. Population parameters and parasitism rate (mean ± SE) of the parasitoid *A. colemani* exposed to thiacloprid + deltamethrin at the LC_{20} = 4.88 g ai/l

Parameters	Control	LC_{20}
The intrinsic rate of increase (r_m; day^{-1})	0.208 ± 0.007 a	0.193 ± 0.008 a
Net reproductive rate (R_0; offspring/individual)	54.64 ± 7.24 a	50.38 ± 6.96 a
Generation time (T; days)	19.22 ± 0.21 b	20.22 ± 0.28 a
C_0 (hosts parasitoid^{-1})	54.66 ± 7.24 a	50.38 ± 6.96 a
Q_p (preys/offspring of predator)	≅1	≅1
ψ (hosts parasitoid^{-1})	0.33 ± 0.11 a	0.21 ± 0.06 a
ω (hosts parasitoid^{-1} day^{-1})	0.41 ± 0.13 a	0.26 ± 0.17 a

SEs were estimated by using the bootstrap technique with 100,000 resampling. Means were compared with the paired bootstrap test (P < 0.05). Lower case letters indicate significant differences between the two treatments.

and *A. flaviventris*. Thiacloprid + deltamethrin reduced demographic parameters of several pest species and their parasitoids, such as the age-stage survival rate, age-specific fecundity, age-specific maternity, and life expectancy (Majidpour *et al*., 2020). Miao *et al*. (2014) also showed that thiacloprid caused a reduction in net reproductive rate, intrinsic rate of increase, finite rate of increase, and an increase in mean generation time of *Sitobion avenae* (Fabricius) (Hemiptera: Aphididae). Similar to the present study, other laboratory studies indicated that sublethal concentrations of imidacloprid and thiamethoxam (LC_{50}, LC_{20}, and LC_1) had no significant effects on the reproduction of *A. colemani* (Ricupero *et al*., 2020).

The negative effects of low concentrations of deltamethrin and thiacloprid on natural enemies were previously reported. A study by Kidd *et al*. (1996) found that the pyrethroid cyhalothrin increased the population growth of *A. gossypii* by reducing the predator population. Similarly, Mardani *et al*. (2016) reported that thiacloprid + deltamethrin had the most negative impact on the life-table parameters of *Lysiphlebus fabarum* (Marshall) (Hymenoptera: Aphididae). In another study, Abdulhay and Rathi (2014) reported that thiacloprid reduced adult emergence and parasitism potency in *Trichogramma evanescens* (Westwood) (Hymenoptera: Trichogrammatidae).

Mead-Briggs (1992) reported that the adult stage was significantly affected by thiacloprid compared to the pre-imaginal stage in *Aphidius rhopalosiphi* (DeStefani-Perez) (Hymenoptera: Braconidae). Bastos *et al*. (2006) investigated *Trichogramma 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 study may be due to differences in the parasitoid species, indicating that *A. flaviventris* is more susceptible than other parasitoids. 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 parameters of this species demographic (Almasi *et al*., 2016).

Thiacloprid belongs to the neonicotinoid group, and this group of insecticides competitively modulates nicotinic insect acetylcholine receptors in insects, while deltamethrin, as pyrethroid insecticide, is a sodium channel modulator in axons of neurons in the nervous system. The neurotoxic activity of both insecticides may also impair reproduction because the reproductive process in arthropods is mediated by neurohormones (Ullah *et al*., 2019). Thus, neurohormonal imbalance due to insecticide poisoning may affect regular reproductive activity. Previous studies attest that adult longevity and fecundity may

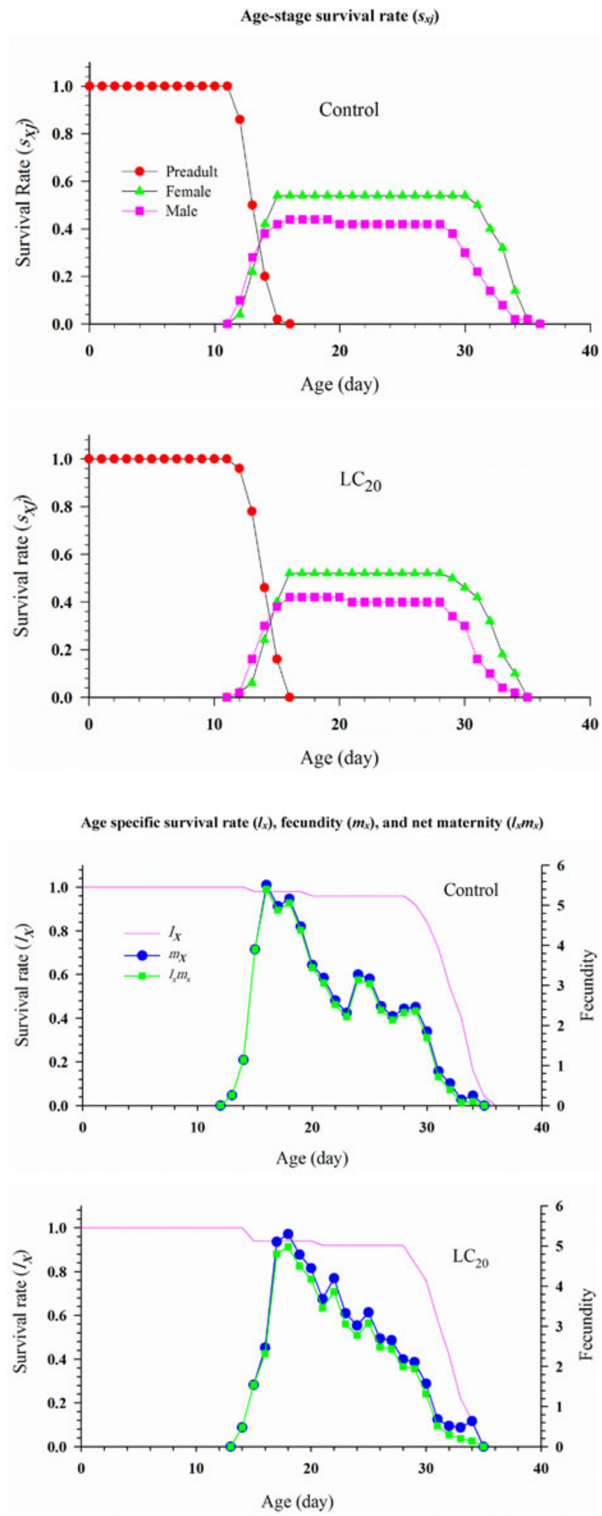

Figure 8. Age-stage survival rate (s_{xj}) and age-specific survival rate (l_x), fecundity (m_x), and net maternity (l_xm_x) of *A. colemani* exposed to thiacloprid + deltamethrin at the LC_{20} = 4.88 g ai/l.

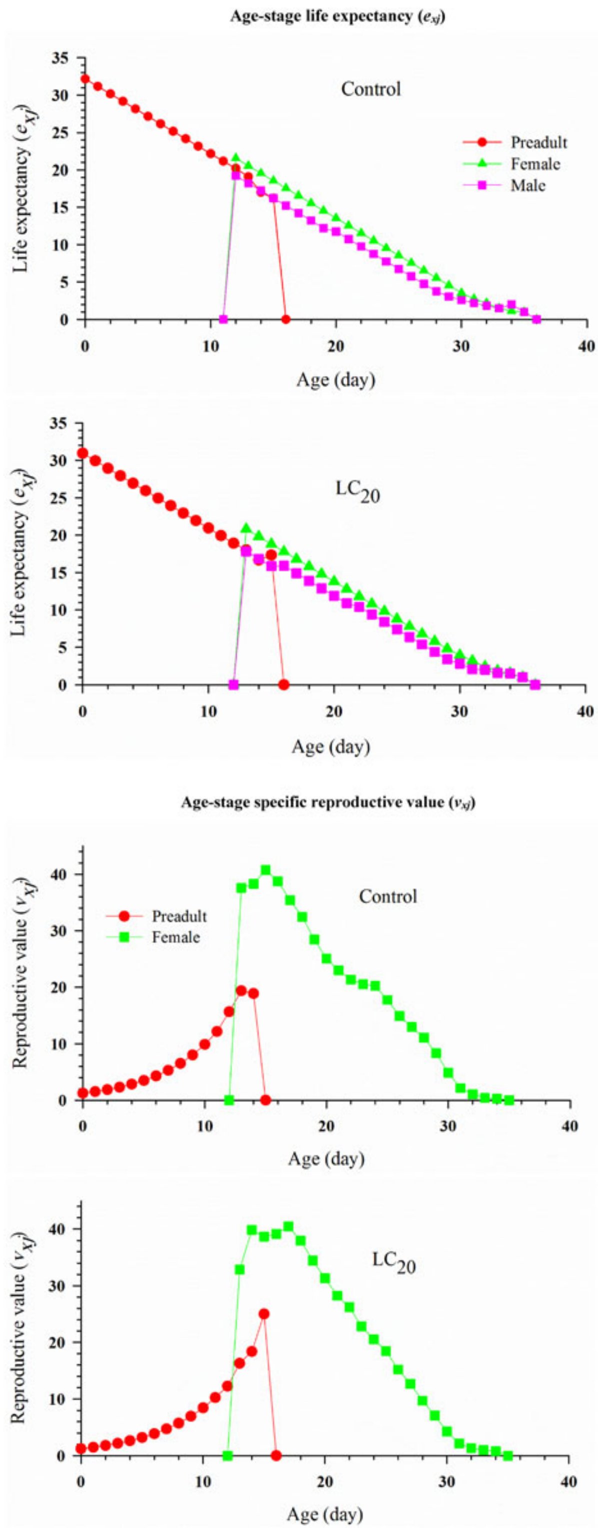

Figure 9. Age-stage life expectancy (e_{xj}) and age-stage specific reproductive value (v_{xj}) of *A. colemani* exposed to thiacloprid + deltamethrin at the LC_{20} = 4.88 g ai/l.

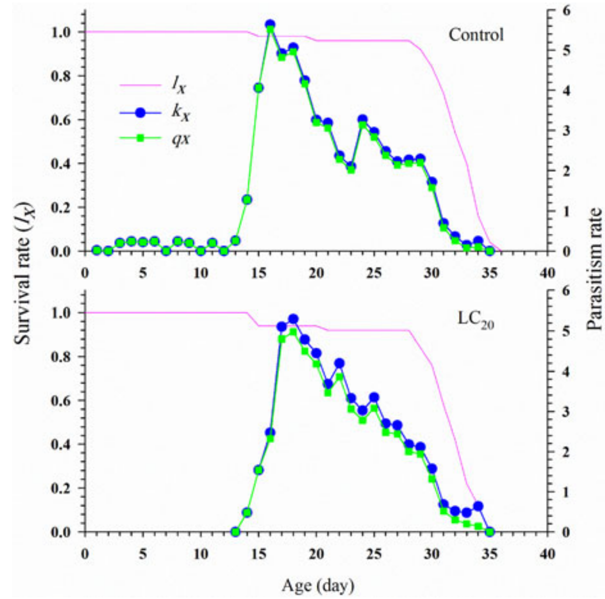

Figure 10. Age-specific survival rate (l_x), age-specific host feeding rate (k_x), and age-specific net host feeding rate (q_x) of *A. colemani* exposed to thiacloprid + deltamethrin at the LC_{20} = 4.88 g ai/l.

be due to disturbances in the neurosecretory system due to sublethal insecticide exposure (Ullah *et al.*, 2019).

Results of the present study indicated that thiacloprid + deltamethrin exhibits high efficiency against *A. gossypii*. The obtained results also showed transgenerational effects of thiacloprid + deltamethrin on the F1 generation of the cotton aphid, reinforcing its efficacy against this species. The significant reductions in the demographic parameters of *A. gossypii* indicated the mixture suitability against this pest species. Nonetheless, this species parasitoid, *A. flaviventris*, was affected even by the low concentration of this insecticide mixture. According to the results obtained, the insecticide compromised all demographic parameters of this parasitoid. In contrast, such effects were only mild on the parasitoid *A. colemani*, which was more tolerant to this insecticide mixture. Based on our findings, thiacloprid + deltamethrin is effective against the cotton aphid *A. gossypii*, but it is also harmful to natural enemies such as *A. flaviventris*, although not as much *A. colemani*. Therefore, the simultaneous use of this insecticide with *A. flaviventris* is not recommended in pest management programs.

Given that this research represents a series of preliminary studies to examine the properties of thiacloprid + deltamethrin, further studies exploring the effect of temperature on insecticide performance against target insect pests and natural enemies are warranted. The assessment of the effects of insecticide mixtures on the insect's detoxification metabolism and behaviors such as dispersal and foraging also deserve attention to better understand their impacts on insects exposed to insecticides.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0007485322000281.

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Conflict of interest. The authors declare that they have no conflict of interest.

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