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# Sublethal effects of spiromesifen on life table traits of *Tetranychus urticae* (Acari: Tetranychidae) and *Neoseiulus californicus* (Acari: Phytoseiidae)

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## Original research

### ABSTRACT

The assessment of long-term negative effects of insecticides on the target and non-target insects can help assess the toxicity and side-effects of pesticides. In this study, the sublethal effects of a low concentration of spiromesifen ( $LC_{20}$ ) on life-history traits of *T. urticae* and its phytoseiid predator *N. californicus* were estimated for two successive generations (F0 and F1). According to the results, adult longevity, oviposition days, fecundity, and life table parameters ( $r_m$ ,  $R_0$ , and  $T$ ) exhibited significant negative impacts at  $LC_{20}$  compared to the control. Meanwhile, significant effects of the  $LC_{20}$  were found on most parameters of the life table (longevity, fecundity, oviposition days) of *N. californicus*. Also, spiromesifen had significant negative effects on the population parameters except for the net reproductive rate ( $R_0$ ) in *N. californicus*. On the other hand, the parameters of the consumption rate (finite predation rate ( $\omega$ ), stable consumption rate ( $\psi$ ), and net consumption rate ( $C_0$ )) in this predator exhibited significant negative impacts. Therefore, the results suggested that spiromesifen effectively controls the successive generation of *T. urticae*. Also, this compound adversely affected most parameters of *N. californicus*, so it is inappropriate for IPM applications in the presence of this parasitoid.

**Keywords** integrated pest management; life table; natural enemy; sublethal effect

## Introduction

The two-spotted spider mite, *Tetranychus urticae* Koch (Acari: Tetranychidae), is one of the most well-known and economically important pests with a broad host plant range in greenhouse and field conditions. Reduced plant vigor, prevention of photosynthesis, webbing, fine stippling, leaf yellowing, leaf drop, and even plant death result from the feeding and sucking of this pest and finally causes considerable yield losses (Li *et al.* 2017; Susurluk and Gürkan 2020; Shang *et al.* 2022).


The biological control by using Phytoseiidae mites is successful in greenhouse conditions (Kang *et al.* 2018; Kumari *et al.* 2017). One of the primary natural enemies used against this pest is *Neoseiulus californicus* (McGregor) (Acari: Phytoseiidae) (Rhodes *et al.* 2006). This natural enemy is a predator of tetranychid mites, particularly *T. urticae* (McMurtry *et al.* 2013). This species is used against *T. urticae* around the world (Sarbaz *et al.* 2017). Nowadays, the integrated pest management strategy uses biological and other controls in complementary ways (Dara 2017). On the other hand, the first way to control this pest is to apply chemical pesticides (Asadi *et al.* 2019). Systemic compounds like spiromesifen from the tetrone acid derivatives group are developed to control this species. Spiromesifen as an insecticidal/acaricidal with a

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specific mode of action is utilized in farms and greenhouses (Asadi *et al.* 2019; Sarbaz *et al.* 2017). This compound acts as a lipid biosynthesis inhibitor (Kumari *et al.* 2017).

Because of several abiotic factors, target and non-target populations receive sublethal concentrations of insecticides in field crops (Dai *et al.* 2021; Guedes *et al.* 2016). The sublethal concentrations can cause impairments in physiological and behavioral attributes (Desneux *et al.* 2007). Meanwhile, the predators can be exposed to pesticides by different approaches like direct contact with spray droplets, consuming the contaminated diet when feeding on food (e.g., pollen, prey), and foliar residues when exploring the crop (Dai *et al.* 2021; Lu *et al.* 2012). Therefore, the assessment of lethal and sublethal effects on these populations are important to be performed (Castro *et al.* 2012; De Castro *et al.* 2013; Maroofpour *et al.* 2021). The life table response experiments are more helpful in predicting the impacts of acaricides on the population of target and non-target species. These experiments reveal the overall impacts and the changes in the population growth rate (Sangak Sani *et al.* 2019). Moreover, the accurate baseline data on the susceptibility of target mite species to acaricides is one of the essential factors in managing acaricides (Kumari *et al.* 2017). There are several studies about the short-term effects of spiromesifen on *T. urticae* and *N. californicus*, whereas the potential long-term influence of this compound has been scarcely investigated (Kumari *et al.* 2017; Phukan *et al.* 2017; Sarbaz *et al.* 2017; Mollaloo *et al.* 2017; Marcic *et al.* 2010). Therefore, this study aimed to assess these general effects in successive generations for *T. urticae* and *N. californicus* exposed to a sublethal dose of spiromesifen.

## Material and methods

### Insecticide

Commercial formulations of spiromesifen (Oberon® SC, 240 g a.i./L), was purchased from Giah Bazr Alvand Co., Iran.

### Biological materials

The original colony of *T. urticae* was obtained from infested cucumber plants collected in cucumber fields at the Yasuj region (Iran). Two-spotted spider mite was continuously reared on cucumber plants (*Cucumis sativus* L. var. Emperor) in the laboratory at  $25 \pm 2$  °C of temperature,  $65 \pm 5\%$  relative humidity (RH), and a photoperiod of 16: 8 h (L: D). Cucumber plants were grown in plastic pots (18 cm in diameter and 19 cm high), and at the seven-leaf stage were used for two-spotted spider mite rearing and all the experiments. The plastic pots were filled by coco peat and perlite (1:1). The mite-infected plants were weekly replaced with new and uncontaminated plants.

The colony of *N. californicus* was purchased from Gyah (Karaj, Iran). Individuals of *N. californicus* were reared on two-spotted spider mite-infested leaves of cucumber plants at  $25 \pm 2$  °C of temperature,  $65 \pm 5\%$  relative humidity (RH), and a photoperiod of 16: 8 h (L: D). The Petri dishes contain cucumber leaf discs (5 cm in diameter) and soaked cotton. New Petri dishes were supplemented at regular intervals (three days) to maintain the culture for experimentation.

### Lethal toxicity on the two-spotted spider mite

The concentration-mortality bioassay was conducted on protonymphs of two-spotted spider mite. Adult females were selected from the population and placed on Petri dishes to establish a synchronous mite culture. After 12 h, the obtained protonymphs were transferred to new Petri dishes to assess the sublethal effects. Six serial concentrations (12, 60, 120, 180, 204 and 240 g a.i./L) of the insecticide were sprayed on the Petri dishes (6 cm in diameter) containing twenty similar-age protonymphs (<12 h old) by using a Potter tower (Burkard Scientific, Uxbridge, UK). The Petri dishes contain cucumber leaf discs (5 cm in diameter) and soaked

cotton. Distilled water was used for the control group. The Petri dishes were kept in the growth chamber maintained at  $25 \pm 2$  °C of temperature,  $65 \pm 5\%$  relative humidity (RH), and a photoperiod of 16:8h (L:D). The two-spotted spider mite mortality was recorded after 48 h, and the experiments were replicated three times.

## **Sublethal effect on the first generation of the two-spotted spider mite**

In this experiment, the sublethal impact of spiromesifen at low concentration ( $LC_{20}$ ) estimated for the protonymphs as described above was carried out on 200 protonymphs (<12 h old) of the two-spotted spider mite. The protonymphs were sprayed with 3 ml of  $LC_{20}$  concentration and distilled water (control treatment) following the methods as mentioned earlier. After 24 h of treatment, 100 surviving protonymphs were transferred to individual Petri dishes containing cucumber leaf discs (5 cm in diameter) along with soaked cotton. The surviving protonymphs were kept there until adulthood. The Petri dishes were observed daily for recorded life table traits (e.g., survival, mortality, and progeny production).

## **Transgenerational effects on life table traits of the two-spotted spider mite**

The fresh eggs ( $\leq 12$  h) were laid by *T. urticae* females exposed to the low concentration ( $LC_{20}$ ). One hundred eggs were transferred to individual Petri dishes containing cucumber leaf discs (5 cm in diameter) along with soaked cotton and maintained until the adult phase at the same conditions as the other experiments. The Petri dishes were checked daily to record life table traits (e.g., survival, mortality, and progeny production).

## **Sublethal effects of spiromesifen on the parental generation of *Neoseiulus californicus***

The sublethal evaluation was carried out on 90 similar-aged female mites (< 24 h old). For this purpose, 3 ml of  $LC_{20}$  concentration and distilled water (control treatment) were sprayed on the leaf discs (5 cm in diameter) using a Potter tower. After 24 h exposure, similar-aged female mites were transferred to the treated leaf discs. Sixty surviving females were removed and transferred to separate clean Petri dishes after 48 h of treatment. Then, females were paired with males and fed with ten protonymphs daily. Females were observed daily until death to calculate fecundity and survival. All experiments were conducted under controlled conditions in a growth chamber at  $25 \pm 2$  °C, 60 – 70% RH, and a photoperiod of 16:8h (L:D).

## **Transgenerational effects and consumption rate of F1 generation of *Neoseiulus californicus***

This investigation was carried out with the fresh eggs obtained from the previous experiment parental. Sixty similar-aged eggs (<12 h old) were transferred to separate Petri dishes and monitored daily until the last mite died. The Petri dishes contain cucumber leaf discs (5 cm in diameter) and soaked cotton. After the emergence of adults, their females and males were paired, and ten protonymphs were daily offered to the predatory mites, and the number of prey mites consumed was recorded. The Petri dishes were kept under controlled conditions in a growth chamber at  $25 \pm 2$  °C, 60 – 70% RH, and a photoperiod of 16:8h (L:D).

## **Statistical analyses**

The data of concentration-response bioassay were subjected to probit analysis using the SPSS software (SPSS 2011), after using Abbott's formula for correction of natural mortality (Abbott 1925). The time-mortality were determined based on Cox regression, with right-censored data and surviving time as independent variables (SPSS, 2011).

The computer program TWOSEX-MS Chart, based on the age-stage, two-sex life-table theory was used to analyze the life-table and population parameters for both mite species (Chi 1988; Chi 2020b; Chi and Su 2006; Chi *et al.* 2020; Tuan *et al.* 2014). The bootstrap technique calculated the standard errors of all population parameters with 100,000 replicates (Chi 2020b).

The CONSUME-MS Chart analyzed daily consumption rates, and the standard errors were calculated through the bootstrap technique with 100,000 replicates (Chi 2020a; Chi and Yang 2003). The consumption parameters estimated were age-specific net consumption rate ( $q_x$ ), net consumption rate ( $C_0$ ), finite predation rate ( $\omega$ ), stable consumption rate ( $\psi$ ), age-specific consumption rate ( $k_x$ ), and transformation rate ( $Q_p$ ).

## Results

### Spiromesifen toxicity against *Tetranychus urticae*

The relative toxicity of spiromesifen to the two-spotted spider mite is shown in Table 1. According to the results, the values 41.01, 133.4, and 803.1 g a.i/L were estimated for  $LC_{20}$ ,  $LC_{50}$ , and  $LC_{90}$ , respectively.

### Sublethal effect on the first generation of the two-spotted spider mite

Sublethal dose of spiromesifen had a negative effect on the development of treated protonymphs (Table 2). The significant effects of the low concentration were observed for most parameters except the adult preovipositional period ( $F = 138.18$ ;  $P = 0.104$ ) and the total preovipositional period ( $F = 35.45$ ;  $P = 0.410$ ). Larva-deutonymph ( $F = 1232.41$ ;  $P < 0.001$ ) and preadult parameters ( $F = 274.6$ ;  $P = 0.046$ ) significantly increased with the insecticide. Meanwhile, total longevity ( $F = 1142.18$ ;  $P < 0.001$ ), oviposition days ( $F = 9870.32$ ;  $P < 0.001$ ), fecundity ( $F = 12093.68$ ;  $P < 0.001$ ), the longevity of females ( $F = 3768.33$ ;  $P < 0.001$ ) and males ( $F = 286.09$ ;  $P < 0.001$ ) showed a significant decrease due to the treatments compared to the control.

Besides, significant differences were also observed in the intrinsic rate of increase ( $r$ ) ( $F = 2433.78$ ;  $P < 0.001$ ), net reproductive rate ( $R_0$ ) ( $F = 3850.44$ ;  $P < 0.001$ ), and generation time ( $T$ ) ( $F = 1218.07$ ;  $P < 0.001$ ) (Table 3). There was no significant effect of spiromesifen in the age-stage survival rate ( $s_{xj}$ ) of each age-stage (Fig. 1). However, the  $LC_{20}$  concentration indicated adverse effects on the age-specific survival rate ( $l_x$ ), the age-specific fecundity ( $m_x$ ) and maternity ( $l_x m_x$ ) (Fig. 2). The egg-laying starting age was delayed, and the peak of fecundity was 5 and 1.8 eggs/female at the control, and  $LC_{20}$ , respectively. Meanwhile, the life expectancy ( $e_{xj}$ ) (Fig. 3) and the age-stage-specific reproductive values ( $v_{xj}$ ) (Fig. 4) were decreased after treatment.

### Transgenerational effects on the two-spotted spider mite

Effects of sublethal dose of spiromesifen on the two-spotted spider mite are presented in Table 2. Based on the results, the treatment of F0 generation by the low concentration of spiromesifen had no significant negative effect on Larva-deutonymph ( $F = 18.99$ ;  $P = 0.605$ ) and preadult parameters ( $F = 123.76$ ;  $P = 0.188$ ) of the F1 generation of *T. urticae*. In contrast, total longevity

**Table 1** Spiromesifen lethal concentration of 20% ( $LC_{20}$ ), 50% ( $LC_{50}$ ) and 90% ( $LC_{90}$ ) of *T. urticae* protonymphs in laboratory bioassays. Mortality was recorded 48 h after exposure.

Treatment	$LC_{20}$ (g a.i/L) (95% CL)	$LC_{50}$ (g a.i/L) (95% CL)	$LC_{90}$ (g a.i/L) (95% CL)	Slope $\pm$ SE	$\chi^2$ (df)	P-value
Spiromesifen	41.01 (23.1-57.6)	133.4 (102.1-158.1)	803.1 (549.2-1542)	1.66 $\pm$ 0.24	8.86 (4)	0.65



( $F = 906.09$ ;  $P < 0.001$ ), the adult preovipositional period ( $F = 285.27$ ;  $P < 0.001$ ), oviposition days ( $F = 2512.95$ ;  $P < 0.001$ ), and fecundity ( $F = 2369.37$ ;  $P < 0.001$ ) were significantly decreased (Table 2). Furthermore, the intrinsic rate of increase ( $r$ ) ( $F = 1203.15$ ;  $P < 0.001$ ), net reproductive rate ( $R_0$ ) ( $F = 2764.73$ ;  $P < 0.001$ ), and generation time ( $T$ ) ( $F = 527.46$ ;  $P = 0.015$ ) of the F1 generation were significantly decreased (Table 3).

The negative effects were observed in the age-stage survival rate ( $s_{xj}$ ) (Fig. 1). The low insecticide concentration decreased the survival rate and adult duration in both sexes of *T. urticae*. Moreover, the  $LC_{20}$  had negative effects on the age-specific survival rate ( $l_x$ ), the age-specific fecundity ( $m_x$ ), and maternity ( $l_x m_x$ ) (Fig. 2). The egg-laying starting age was delayed, and the peak of fecundity was 3.4 and 1.7 eggs/female at the control, and  $LC_{20}$ , respectively. Meanwhile, the life expectancy ( $e_{xj}$ ) (Fig. 3) and the age-stage-specific reproductive values ( $v_{xj}$ ) (Fig. 4) were decreased after treatment with the low insecticide concentration.

### Sublethal effects on the parental generation of *Neoseiulus californicus*

The sublethal effects on the F0 generation of *N. californicus* are reported in Table 4. The longevity of female adults ( $F = 12712.18$ ;  $P < 0.001$ ), fecundity ( $F = 9259.92$ ;  $P < 0.001$ ), and oviposition days ( $F = 15388.94$ ;  $P < 0.001$ ) significantly decreased after exposure. Meanwhile, the net reproductive rate ( $F = 9259.92$ ;  $P < 0.001$ ), and generation time ( $F = 1960.70$ ;  $P < 0.001$ ) was significantly decreased except the intrinsic rate of increase ( $F = 184.04$ ;  $P = 0.062$ ). Based on the results, the start of egg-laying was delayed in the low insecticide concentration. On the other hand, the highest age-specific fecundities were decreased in the  $LC_{20}$  (1.7 eggs/female)

**Table 2** Life table parameters (mean  $\pm$  SE) of two generations of two-spotted spider mite *Tetranychus urticae* exposed (F0) and unexposed (F1) with an  $LC_{20}$  (41.01 g a.i/L) of spiromesifen in laboratory bioassays.

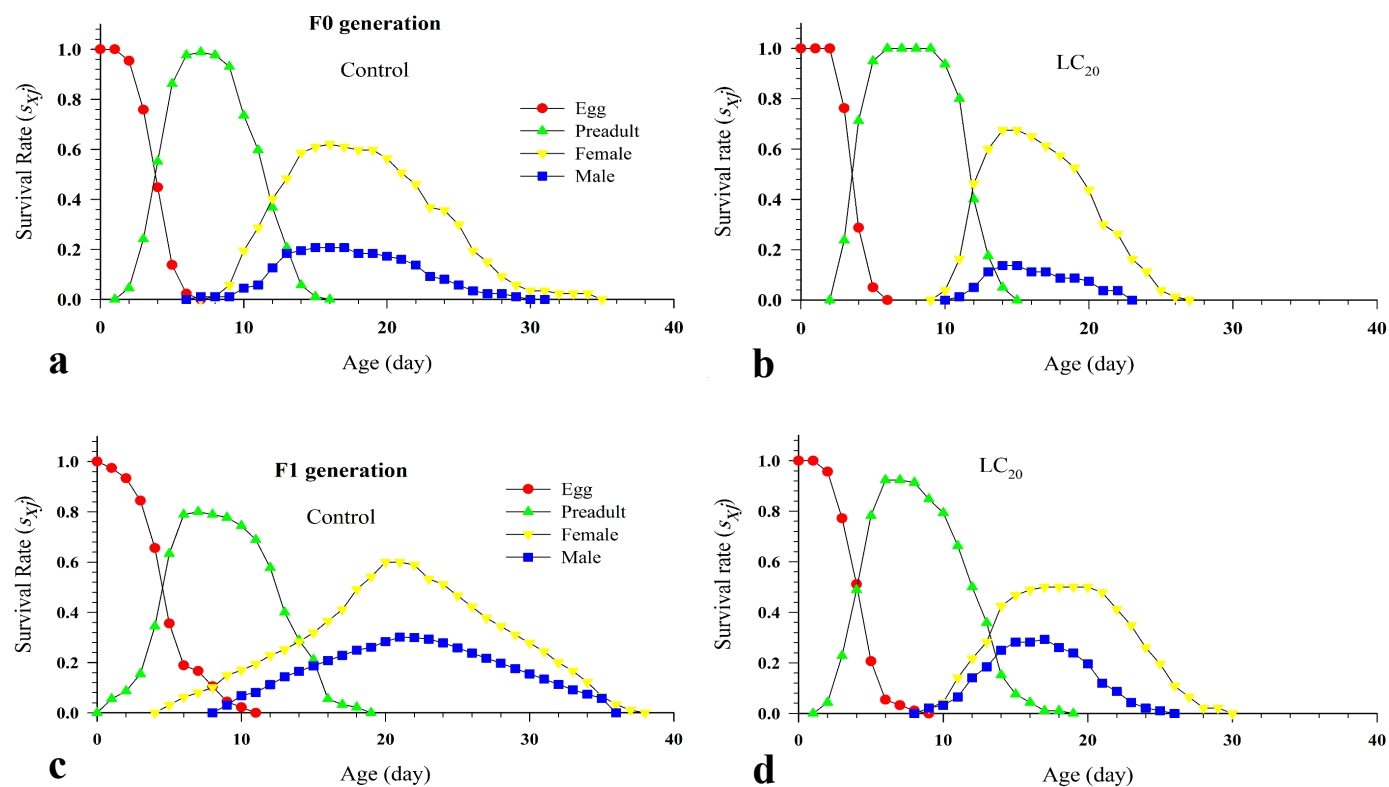
Parameters	Treatment			
	F0		F1	
	Control	$LC_{20}$	Control - F1 from F0 untreated	$LC_{20}$ - F1 from F0 treated
	Mean $\pm$ SE	Mean $\pm$ SE	Mean $\pm$ SE	Mean $\pm$ SE
Longevity of egg (d)	4.32 $\pm$ 0.12 a	4.1 $\pm$ 0.09 a	4.72 $\pm$ 0.19 a	4.33 $\pm$ 0.12 a
Larva-deutonymph (d)	7.28 $\pm$ 0.17 b	8.12 $\pm$ 0.11 a	8.6 $\pm$ 0.31 a	8.45 $\pm$ 0.17 a
Longevity of male adult (d)	11.72 $\pm$ 0.75 a	7.27 $\pm$ 0.63 b	16.44 $\pm$ 1.31 a	8.63 $\pm$ 0.35 b
Longevity of female adult (d)	13.28 $\pm$ 0.38 a	8.84 $\pm$ 0.38 b	15.93 $\pm$ 0.67 a	12 $\pm$ 0.32 b
Preadult (d)	11.79 $\pm$ 0.22 b	12.73 $\pm$ 0.27 a	13.3 $\pm$ 0.34 a	12.78 $\pm$ 0.22 a
Longevity (d)	22.54 $\pm$ 0.62 a	19.66 $\pm$ 0.46 b	24.48 $\pm$ 0.97 a	20.84 $\pm$ 0.32 b
Adult pre-ovipositional period (d)	0.74 $\pm$ 0.12 a	0.49 $\pm$ 0.1 a	1.29 $\pm$ 0.30 b	1.81 $\pm$ 0.21 a
Total pre-ovipositional period (d)	12.5 $\pm$ 0.27 a	12.76 $\pm$ 0.18 a	14.54 $\pm$ 0.38 a	14.53 $\pm$ 0.31 a
Oviposition days	9.96 $\pm$ 0.33 a	4.14 $\pm$ 0.29 b	11.23 $\pm$ 0.62 a	6.23 $\pm$ 0.32 b
Fecundity (offspring/adult)	43.5 $\pm$ 1.81 a	11.44 $\pm$ 1.24 b	44.35 $\pm$ 3.02 a	20.65 $\pm$ 1.6 b

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

**Table 3** Population parameters (mean  $\pm$  SE) of the two-spotted spider mite *Tetranychus urticae* sublethally exposed to spiromesifen (41.01 g a.i/L).

Parameter	F0		F1	
	Control	$LC_{20}$	Control - F1 from F0 untreated	$LC_{20}$ - F1 from F0 treated
The intrinsic rate of increase ( $r_m$ ; day $^{-1}$ )	0.192 $\pm$ 0.006 a	0.134 $\pm$ 0.008 b	0.171 $\pm$ 0.007 a	0.131 $\pm$ 0.007 b
Net reproductive rate ( $R_0$ ; offspring/individual)	27 $\pm$ 2.52 a	8.15 $\pm$ 1.04 b	28.08 $\pm$ 2.95 a	10.32 $\pm$ 1.32 b
Generation time ( $T$ ; day)	17.10 $\pm$ 0.34 a	15.56 $\pm$ 0.21 b	19.46 $\pm$ 0.61 a	17.80 $\pm$ 0.32 b

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



**Figure 1** Age-stage survival rate ( $s_{xj}$ ) of two generations of *Tetranychus urticae* exposed to LC<sub>20</sub> of spiromesifen.

compared to the control (3.4 eggs/female) (Fig. 5).

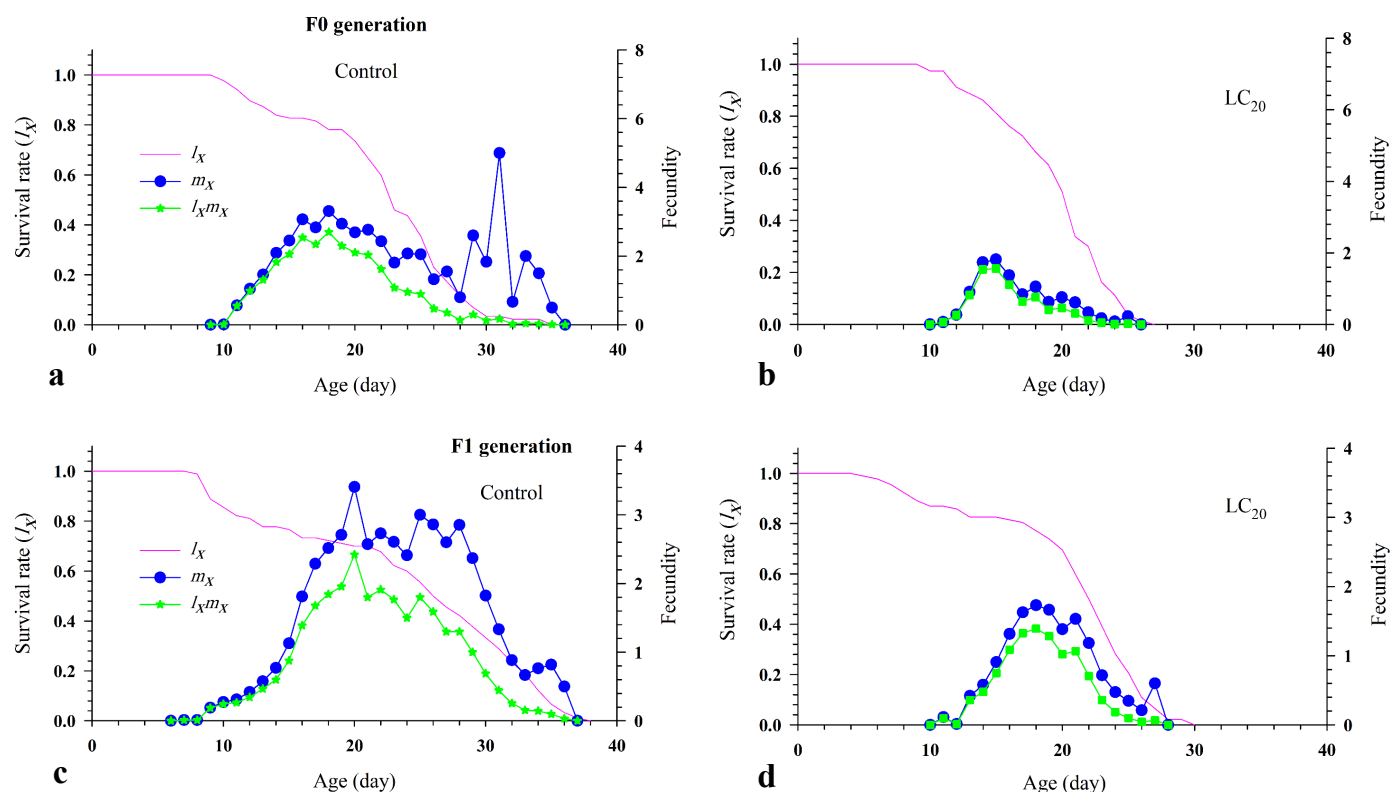
**Transgenerational effects and consumption rate of F1 generation of *Neoseiulus californicus***

Spiromesifen had negative effects on the life-history traits in F1 from F0 treated generation of *N. californicus* (Table 5). The significant decrease registered for larva-deutonymph (F=

**Table 4** Life table parameters (mean  $\pm$  SE) of the predator *Neoseiulus californicus* parental generation sublethally exposed to spiromesifen (41.01 g a.i/L).

Parameter	Treatment	
	Control	LC <sub>20</sub>
	Mean $\pm$ SE	Mean $\pm$ SE
Longevity of female adult (d)	34.77 $\pm$ 0.46 a	26.16 $\pm$ 0.35 b
Fecundity (offspring/adult)	60.04 $\pm$ 1.5 a	37.16 $\pm$ 0.98 b
Oviposition days	32.08 $\pm$ 0.46 a	21.6 $\pm$ 0.43 b
The intrinsic rate of increase ( $r_m$ ; day <sup>-1</sup> )	0.234 $\pm$ 0.002 a	0.226 $\pm$ 0.003 a
Net reproductive rate ( $R_0$ ; offspring/individual)	60.1 $\pm$ 1.5 a	37.1 $\pm$ 0.9 b
Generation time ( $T$ ; day)	17.4 $\pm$ 0.1 a	15.9 $\pm$ 0.2 b

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



**Figure 2** Age specific survival rate ( $l_x$ ), fecundity ( $m_x$ ), and net maternity ( $l_x m_x$ ) of two generations of *Tetranychus urticae* exposed to  $LC_{20}$  of spiromesifen.

212.73;  $P = 0.037$ ), preadult ( $F = 569.67$ ;  $P < 0.001$ ), adult preovipositional period ( $F = 206.13$ ;  $P = 0.015$ ), oviposition days ( $F = 566.17$ ;  $P < 0.001$ ), and fecundity ( $F = 1598.24$ ;  $P < 0.001$ ). Whereas there was no significant difference in longevity of egg ( $F = 198.74$ ;  $P = 0.051$ ), total longevity ( $F = 4.18$ ;  $P = 0.77$ ), total preovipositional period ( $F = 31.71$ ;  $P = 0.34$ ), and longevity of female ( $F = 1.75$ ;  $P = 0.82$ ) and male ( $F = 1.07$ ;  $P = 0.77$ ). Moreover, the  $LC_{20}$  significantly decreased the intrinsic rate of increase ( $F = 319.83$ ;  $P = 0.015$ ) and generation time ( $F = 729.20$ ;  $P < 0.001$ ) (Table 6).

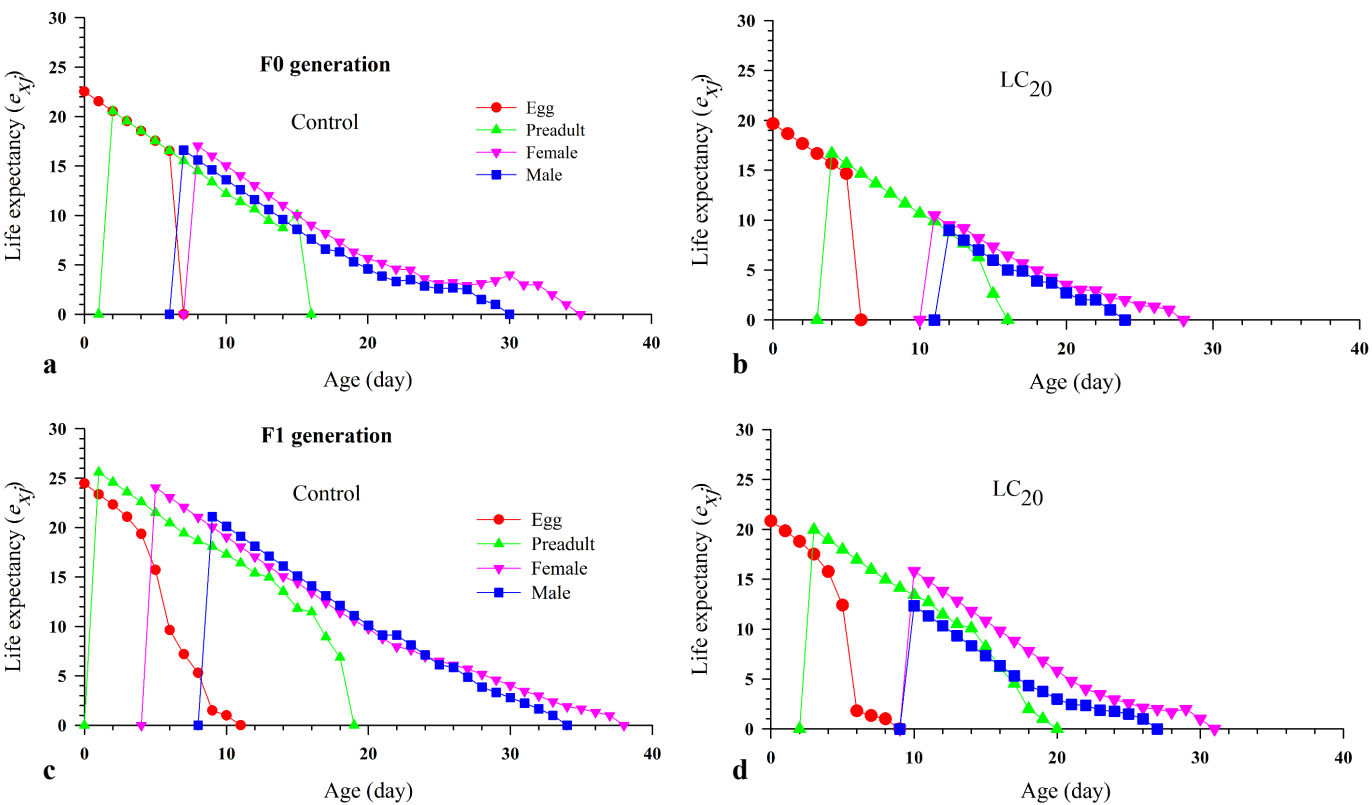
Accordingly to results, there was no negative effect on the age-stage survival rate ( $s_{xj}$ ) of each mite age-stage and the age-specific survival rate ( $l_x$ ), the age-specific fecundity ( $m_x$ ), and maternity ( $l_x m_x$ ) (Fig. 1 and 2). Furthermore, the  $LC_{20}$  had no negative effect on the life expectancy ( $e_{xj}$ ) (Fig. 6) and the age-stage-specific reproductive values ( $v_{xj}$ ) (Fig. 7).

The sublethal effects on the consumption rate of *N. californicus* are summarized in Table 6. The low insecticide concentration significantly decreased net consumption rate ( $C_0$ ) ( $F = 764.97$ ;  $P < 0.001$ ), finite predation rate ( $\omega$ ) ( $F = 751.99$ ;  $P < 0.001$ ), stable consumption rate ( $\psi$ ) ( $F = 668.86$ ;  $P < 0.001$ ), except transformation rate ( $Q_p$ ) ( $F = 22.83$ ;  $P = 0.49$ ) (Table 6). Subsequently, The  $LC_{20}$  decreased the age-specific parasitism rate ( $k_x$ ) and age-specific net parasitism rate ( $q_x$ ).

## Discussion

Towards the rational application of insecticides, investigation on the effects of insecticides is an essential issue because insect populations are frequently exposed to lethal or sublethal concentrations of insecticides in the field (Guedes *et al.* 2016; Majidpour *et al.* 2020). Limited





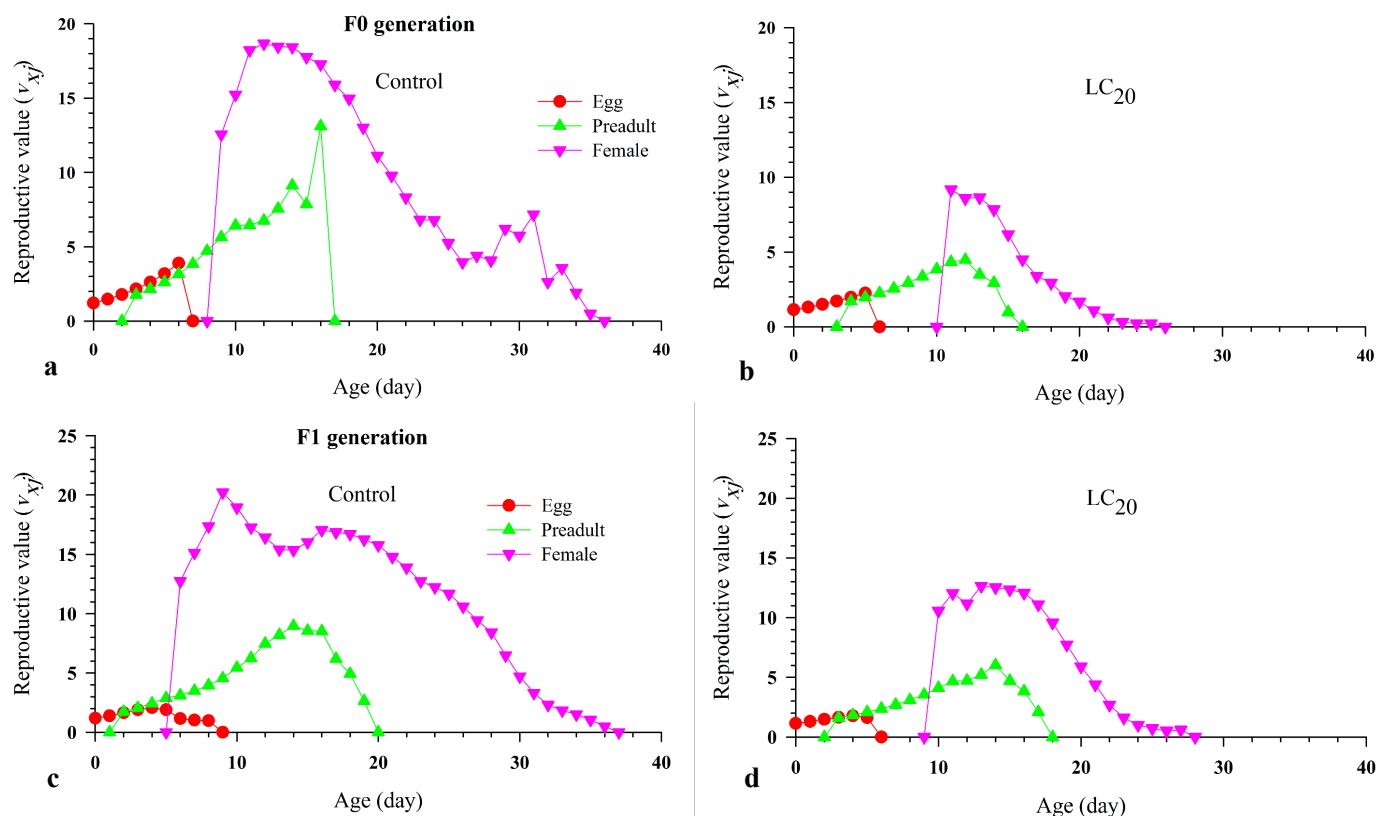
**Figure 3** Age-stage life expectancy ( $e_{xj}$ ) of two generations of *Tetranychus urticae* exposed to LC<sub>20</sub> of spiromesifen.

studies have been conducted separately on the effects of spiromesifen on *T. urticae* and their natural enemies, most of which have been on the first generation of insects (Kumari *et al.* 2017; Marcic *et al.* 2010, 2009; Mollaloo *et al.* 2017; Sarbaz *et al.* 2017). A comprehensive

**Table 5** Life table parameters (mean  $\pm$  SE) of the predator *Neoseiulus californicus* sublethally exposed (F0) and unexposed (F1) with an LC<sub>20</sub> (41.01 g a.i/L) of spiromesifen in laboratory bioassays.

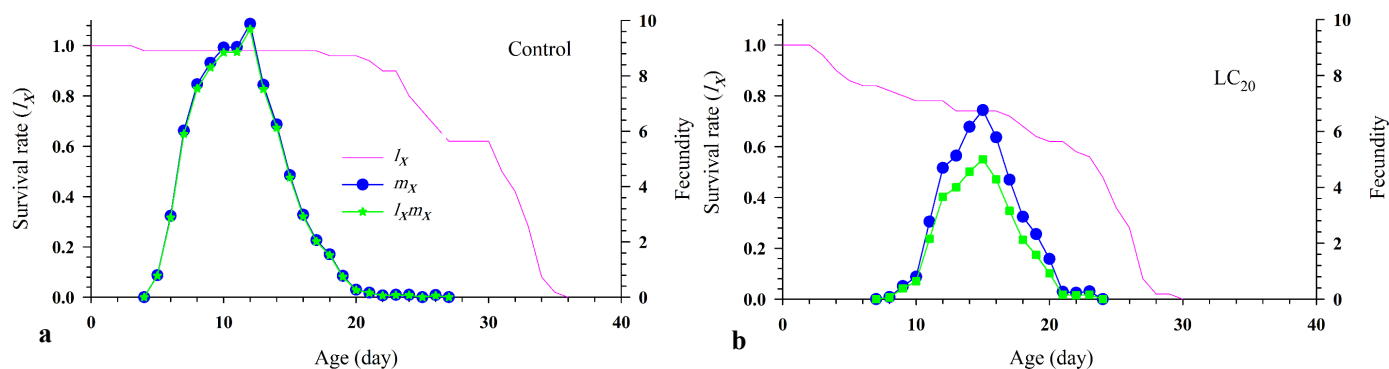
Stage	Treatment	
	Control	F1 - from treated generation
	Mean $\pm$ SE	Mean $\pm$ SE
Longevity of egg (d)	1.75 $\pm$ 0.06 a	1.57 $\pm$ 0.07 b
Larva-deutonymph (d)	6.79 $\pm$ 0.08 a	6.49 $\pm$ 0.12 b
Longevity of male adult (d)	25.43 $\pm$ 0.92 a	25.77 $\pm$ 0.79 a
Longevity of female adult (d)	36.42 $\pm$ 0.86 a	36.67 $\pm$ 0.78 a
Preadult (d)	8.53 $\pm$ 0.1 a	8.06 $\pm$ 0.11 b
Longevity (d)	39.68 $\pm$ 1.46 a	40.23 $\pm$ 1.33 a
Adult preovipositional period (d)	0 $\pm$ 0 b	0.23 $\pm$ 0.09 a
Total preovipositional period (d)	8.45 $\pm$ 0.12 a	8.28 $\pm$ 0.15 a
Oviposition days	33.94 $\pm$ 0.78 a	29.8 $\pm$ 0.73 b
Fecundity (offspring/adult)	64.33 $\pm$ 1.7 a	50.2 $\pm$ 1.36 b

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

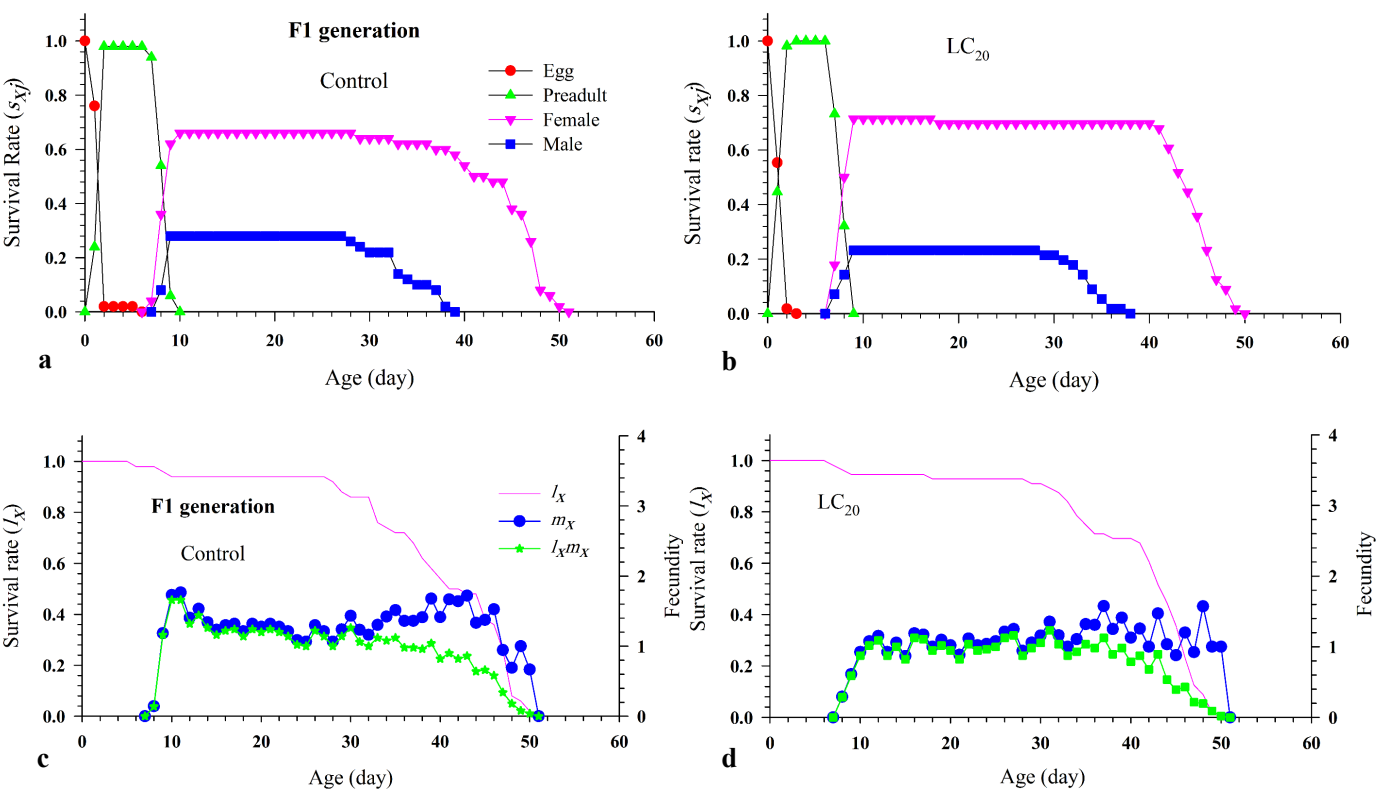


**Figure 4** Age-stage specific reproductive value ( $v_{xj}$ ) of two generations of *Tetranychus urticae* exposed to  $LC_{20}$  of spiromesifen.

evaluation of the total impact on insect populations is essential to include the short-term effects of insecticides and the impact on the next generation, which can have important implications for the success of an IPM program (Müller 2018; Ali *et al.* 2017). Our study has clarified the sublethal effects of pesticides on both pests and their natural enemies in successive generations, how residual pesticides affect natural enemies, and how natural enemies respond to environmental xenobiotics. Based on the results, spiromesifen had a significant negative effect



**Figure 5** Age specific survival rate ( $I_x$ ), fecundity ( $m_x$ ), and net maternity ( $I_x m_x$ ) of *Neoseiulus californicus* exposed to  $LC_{20}$  of spiromesifen.



**Figure 6** Age-stage survival rate ( $s_{xj}$ ) and age specific survival rate ( $l_x$ ), fecundity ( $m_x$ ), and net maternity ( $l_x m_x$ ) of *Neoseiulus californicus* exposed to LC<sub>20</sub> of spiromesifen.

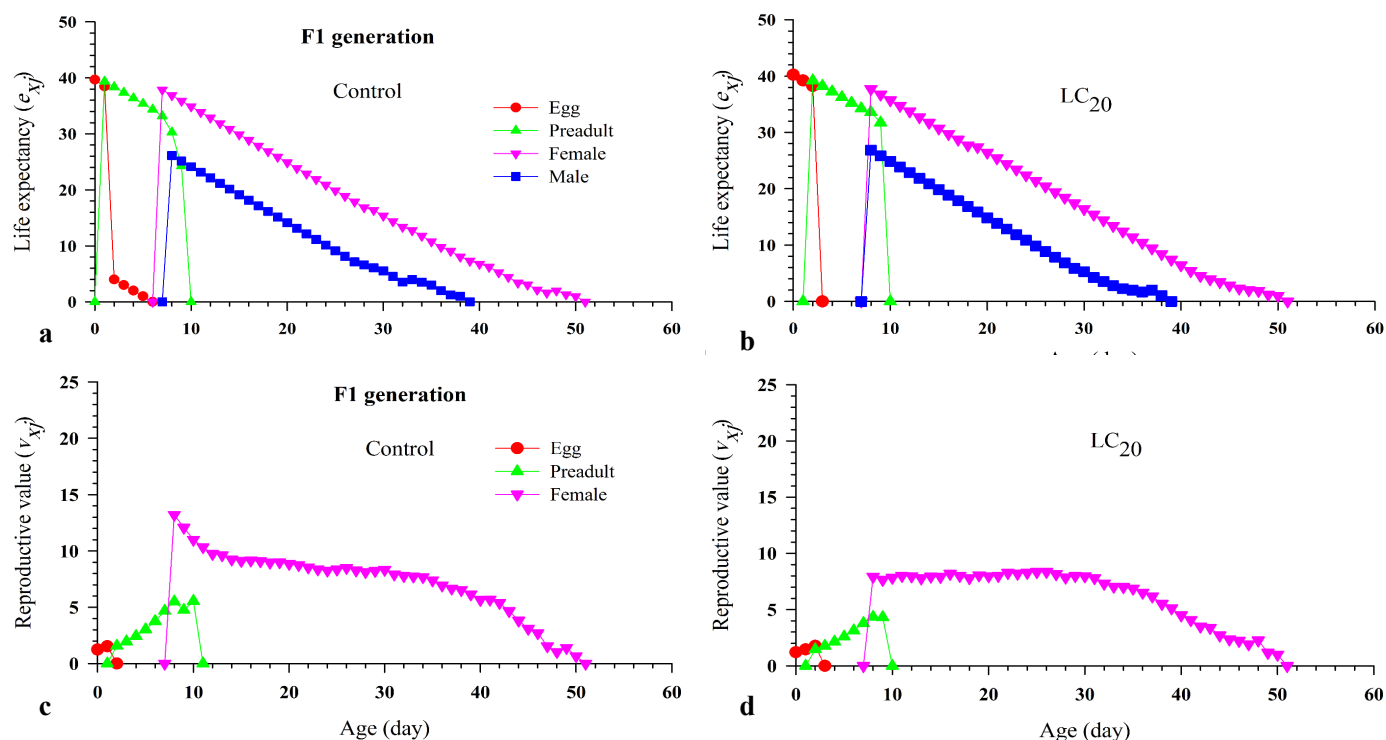
on most life table parameters of the pest population. These results showed this pesticide had suitable control in the successive generation of *T. urticae*. Besides, the LC<sub>20</sub> concentration had a significant negative effect on most life table parameters of *N. californicus* in the successive generation.

Consistent with the present study, spiromesifen showed high toxicity in the female stages

**Table 6** Population parameters and consumption rate (mean ± SE) of the predator *Neoseiulus californicus* exposed (F0) and unexposed (F1) with an LC<sub>20</sub> (41.01 g a.i/L) of spiromesifen in laboratory bioassays.

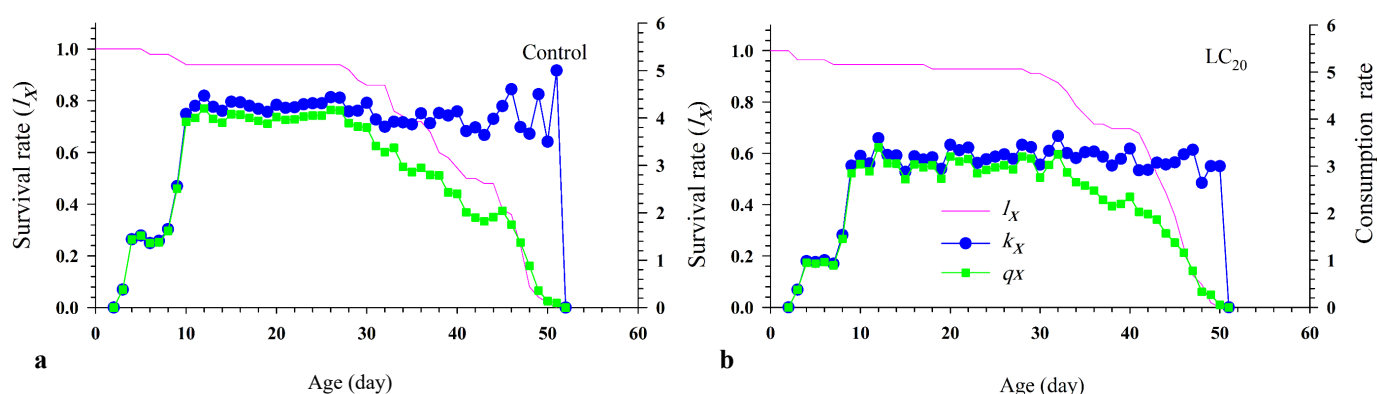
Parameter	Treatment	
	Control	F1 - from treated generation
	Mean ± SE	Mean ± SE
Intrinsic rate of population growth (day <sup>-1</sup> )	0.2176 ± 0.01 a	0.1906 ± 0.01 b
Net reproductive rate (offspring/individual)	42.46 ± 4.45 a	35.85 ± 3.17 a
Generation time ( <i>T</i> ; day)	17.22 ± 0.26 b	18.77 ± 0.31 a
<i>C</i> <sub>0</sub> (hosts parasitoid <sup>-1</sup> )	137.64 ± 6.25 a	108.88 ± 4.40 b
<i>Q</i> <sub><i>p</i></sub> (preys/offspring of predator)	3.24 ± 0.26 a	3.03 ± 0.20 a
<i>ψ</i> (hosts parasitoid <sup>-1</sup> )	1.21 ± 0.03 a	1.07 ± 0.02 b
<i>ω</i> (hosts parasitoid <sup>-1</sup> day <sup>-1</sup> )	1.50 ± 0.04 a	1.29 ± 0.03 b

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



**Figure 7** Age-stage life expectancy ( $e_{xy}$ ) and age-stage specific reproductive value ( $v_{xy}$ ) of *Neoseiulus californicus* exposed to  $LC_{20}$  of spiromesifen.

of the two-spotted spider mite in one-third of the recommended concentration (Kumari *et al.* 2017). In another study, spiroticlofen had a significant negative impact on most parameters (development time, longevity and fecundity) of *T. urticae* in the different sublethal concentrations ( $LC_5$ ,  $LC_{15}$  and  $LC_{35}$ ) (Sangak Sani *et al.* 2019). The obtained results of the present study are in the same line as those reported by Kumari *et al.* (2017) and Sangak Sani *et al.* (2019). Similarly, Phukan *et al.* (2017) reported that spiromesifen in the recommended concentration cause reduced the fecundity potential in females and the mite population of *T.*



**Figure 8** Age-specific survival rate ( $I_x$ ), age-specific host feeding rate ( $k_x$ ) and age-specific net host feeding rate ( $q_x$ ) of the predator *Neoseiulus californicus* exposed to  $LC_{20}$  of spiromesifen.

*urticae* decreased consequently. Meanwhile, (Marcic *et al.* 2010) showed that spiromesifen at different concentrations had a significant negative impact on the fecundity and net fertility of *T. urticae*. In another study, Marcic *et al.* (2009) recorded that the two-spotted spider mite population growth rates and fecundity were significantly reduced after exposure with spiromesifen. Besides, Marcic (2007) reported that spiroticlofen significantly affected the survival rate and total fecundity of *T. urticae*. Consistent with the present study, some investigations demonstrated that spiromesifen have toxicity and pronounced residual effects on the fecundity and development stages of *T. urticae* (Dekeyser 2005; Nauen and Schnorbach 2005; Sato *et al.* 2011; Wachendorff *et al.* 2002). Overall, the previous assessments only showed adverse effects of spiromesifen in the first generation on *T. urticae*, but the present study demonstrated that this compound has appropriate long-term effects for influencing the pest population.

On the other hand, the effects of spiromesifen have been studied in different natural enemies. A study by Sarbaz *et al.* (2017) demonstrated that spiromesifen and spiroticlofen at different concentrations decreased the longevity of *N. californicus*. They also reported that spiromesifen and spiroticlofen affected the intrinsic rate of increase ( $r$ ) and net reproductive rate ( $R_0$ ), and these parameters decreased after exposure. In another study, the low concentrations ( $LC_{50}$ ,  $LC_{10}$ , and  $LC_{15}$ ) of spiromesifen significantly decreased the longevity and population parameters (except mean generation time ( $T$ )) of *N. californicus*. However, this compound had no significant negative effects on the development stage of this predator (Mollaloo *et al.* 2017). In consistence with the present study, Lee and Kim (2015) found that spiroticlofen, spiromesifen did not affect the egg stage of *N. californicus*. Meanwhile, low toxicity was recorded for the nymphs, adult females, and reproduction. The reduced food uptake due to acaricide effects might partially explain these reductions (Hamed *et al.* 2009). Our results are in line with Cloyd *et al.* (2006), who reported that spiromesifen decreased the longevity in *N. californicus*. Moreover, reduction of the intrinsic rate of population growth ( $r$ ) in females of *N. californicus* was recorded when this predator was exposed to spiroticlofen and fenazaquin (Maroufpoor *et al.* 2016). However, the low concentrations of spiroticlofen ( $LC_{10}$ ,  $LC_{20}$ , and  $LC_{30}$ ) had no significant effect on population parameters of offspring *Amblyseius swirskii* Athias-Henriot (Acari: Phytoseiidae) (Alinejad *et al.* 2016). This contrast may be due to species differences, different susceptibility of phytoseiid species, experimental conditions, and tested acaricides.

## Conclusion

According to the results, spiromesifen is highly toxic to the two-spotted mite, even at low concentration. On the other hand, the adverse effects of this insecticide affected the subsequent generation. Meanwhile, this compound negatively affected the different generations of *N. californicus*. Overall, the obtained results of this research under laboratory conditions emphasized the significance of evaluating sublethal effects of spiromesifen on the two-spotted mite and its predator *N. californicus* and determining how these effects may be interpreted to population dynamics in the field. Further research into spiromesifen's impact on target and non-target organisms under semi-field and field conditions is vital to improving our understanding of pest management by considering the interaction of chemical and biological control.

## Conflict of interest

The authors declare that they have no conflict of interest.

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