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Toxicity and Sublethal Effects of Selected Insecticides on Life Table Parameters of Greenhouse Whitefly (*Trialeurodes vaporariorum*) and its Parasitoid *Encarsia formosa*

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ABSTRACT

Greenhouse whitefly, *Trialeurodes vaporariorum* Westwood (Hemiptera: Aleyrodidae), is a serious greenhouse pest. Due to its morphological features and the potential of resistance to chemical insecticides, it is necessary to find suitable and compatible compounds for the integrated control of this pest that has the least adverse effect on its parasitoid, *Encarsia formosa* Gahan (Hymenoptera: Aphelinidae). In this research, sublethal effects of emamectin, spinosad and buprofezin on *T. vaporariorum* and its parasitoid *E. formosa* was investigated. The result of sublethal effect of insecticides on *T. vaporariorum* showed that all insecticides used effected whitefly biological parameters (the period of immature stages, reproduction, longevity and consequently generation population growth rate). The most sublethal effects were observed in buprofezin. Buprofezin significantly reduced net reproduction rate(R_0), intrinsic rate of population growth(r_m), finite rate of population growth(λ) while the duration of generation (T) was increased. Emmamectin benzoate significantly reduced the life table parameters of parasitoid, *E. formosa*. Due to negative effects of buprofezin on *T. vaporariorum* and the least negative effect on *E. formosa*, in the management control of whitefly, this insecticide is recommended.

INTRODUCTION

The greenhouse whitefly, *Trialeurodes vaporariorum*, is a major pest of greenhouse crops worldwide (He *et al.*, 2018; Drobnjakovic and Marcic, 2021). Whiteflies causes extensive crop damage by feeding and virus transmission. Controlling this noxious pest can be challenging due to pest resistance to readily available pesticides (Fytrou *et al.*, 2017). The use of biological control as part of IPM programs has been adopted worldwide as a good tactic to improve crop protection and reduce pesticide use (Fytrou *et al.*, 2017). The most widely used parasitoid to control *T. vaporariorum* in greenhouses is *Encarsia formosa* (Hymenoptera: Aphelinidae). Females of *E. formosa* are the primary endoparasitoids of greenhouse whiteflies (Drobnjaković *et al.*, 2019). Evaluating the affect of chemical pesticides on parasitoids is necessary because the effectiveness of biological control is reduced by these compounds. Insecticide application in IPM program should be toxic to target pests and non-risk to beneficial insects (Torre and Bueno, 2018). Whitefly control by *E. formosa* is successful when the growth rate of parasitoid in the presence of the parasitoid is greater than the pest (Drobnjakovic and Marcic, 2021). Pesticide treatment is necessary when parasitoids cannot control pest populations. Whitefly resistance to various compounds has increased with the widespread use of chemical insecticides in the world (Drobnjakovic *et al.*, 2019) and Iran (Shafaei *et al.*, 2021). Pest management programs aim to reduce the high mortality of natural enemies by ecofriendly pesticides (Moadeli *et al.*, 2014). Spinosad is a relatively new class of insecticide compared to traditional options, which has shown its effectiveness against many pests and whitefly (Shafaei *et al.*, 2021). It is made by the soil actinomycete, *Saccharopolyspora spinosa* and is a natural mixture of spinosyn A and spinosyn D (Moadeli *et al.*, 2014). This insecticide affects by contact and digestion. It causes the activity of nicotinic acetylcholine

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and gamma-aminobutyric acid receptors, which stops feeding, reduces body fluids, and paralyzes the insect (Gress and Zalom, 2017). Also, emamectin benzoate is a member of the avermectin family, and product of the *Streptomyces avermitilis* (Stavrakaki *et al*., 2022). The mode of action is the stimulation of high - affinity GABA receptors and then increase chloride ion permeability (Sallard *et al*., 2021). Buprofezin is a chitin synthesis inhibitor and is widely used against several sucking pests with very low risk to the environment (Ullah *et al*., 2019). Using chemical insecticides that have side effects on beneficial insects can lead to pest outbreaks (Drobnjakovic and Marcic, 2021). Investigating the side effects of chemical compounds on the natural enemies is important for finding suitable compounds for use in IPM programs (Chitgar and Ghadamyari, 2013). In order to study the wide impact that insecticides have on insects, it is necessary to investigate the effects of their lethal and sublethal concentrations (Nozad-Bonab *et al*., 2021). Demographic toxicology is the best way to evaluate effects of pesticides on insects (Rafiee-Dastjerdi *et al*., 2012). Sublethal effects are defined as biological, physiological, demographic or behavioral effects on individuals or populations that survive exposure to a toxicant at lethal or sublethal concentration. A sublethal concentration is defined as inducing no apparent mortality in the experimental population (Desneux *et al*., 2007). In general, insecticide concentrations under the (LC_{50}) are considered to be sublethal. The sublethal effects may be manifested as reductions in life span, development rates, population growth, fertility, fecundity, changes in sex ratio, deformities, changes in behavior, feeding, searching and oviposition (Lee, 2000). Among the important strategies in greenhouse whitefly control is the use of biological insecticides and insecticides with the greatest negative effect on the pest and the least risk on parasitoids (Gholamzadeh *et al*., 2012).

Therefore, in this study, the sub-lethal effects of spinosad, emamectin and buprofezin from different group of insecticides, on the biological parameter table of *T. vaporariorum* and *E. formosa* were investigated.

MATERIALS AND METHODS

Study sites and experimental design

In 2021 and 2022, the cultivation of plants was carried out in the greenhouses and farms of the Islamic Azad University of Mahabad. Also sublethal experiments were carried out in university laboratories in Mahabad city (36° 45′ 40.64″ N, 45° 44′ 43.47″ E and 1385 meters above sea level) in West Azarbaijan province in Iran.

Insecticides

Emamectin benzoate (Proclaim® 5% SG, 100/ha) manufactured (Syngenta, Switzerland), with IRAC class 6 and MoA Glutamate-gated chloride channel (GluCl) allosteric modulators, Spinosad (Tracer® 24% SC, 50ml/400 l) manufactured (Dow Agrosciences) with the content of Spinosyn A and Spinosyn D, with IRAC class 5 and MoA Nicotinic acetyl-choline receptor (nAChR) allosteric modulators and Buprofezin (Applaud® 24% SC, 200 ml/400 l) manufactured (Nihon Nohyaku, Japan) with IRAC class 16 and MoA Inhibitors of chitin biosynthesis were used.

Plant cultivation

For the cultivation of green bean, *Phaseolus vulgaris* L. (Fabaceae) in the greenhouse, commercial cultivars Sunray, was obtained from the research center of West Azerbaijan province and cultivated under greenhouse conditions (16: 8 light/ dark cycle, temperature of 27 ± 2 °C and relative humidity of 65 ± 5%). Plastic pots measuring 6 × 7 × 8 cm were used for planting. The soil used to grow the host plant was a mixture of garden soil, sand, and leaf soil in the ratio of 1, 3 and 5 parts, respectively.

Insect rearing

The same-aged plants (≈ 6-8 leaf stages) were selected for rearing *T. vaporariorum* as well as experimentations. Sensitive population of *T. vaporariorum* were reared for three generations from insects collected in greenhouses on bean plants in Mahabad, Iran. The plants infected with *T. vaporariorum* were kept in fine mesh cages (150 × 90 × 90 cm) and healthy plants were regularly added into these cages every week. To maintain the vigor of the whiteflies, the samples collected from the same regions were periodically added to the stock colony.

Pupal stage of *E. formosa* were collected from greenhouses without a history of using commercial parasitoid on Ph. vulgaris. The emerged female wasps were reared on *T. vaporariorum* hosts at (16: 8 light/ dark cycle, temperature of 27 ± 2 °C and relative humidity of 65 ± 5%).

Lethal effects of insecticides on nymphs of T. vaporariorum

The lethal effect of insecticides was assessed on third-instars nymphs. The experimental concentrations of insecticides are shown in Table II. For each treatment 20 individuals were used. Control insects were treated with distilled water. A leaf disc with 20 third-instar nymphs were cut off from fully expanded green bean leaves and dipped for 30 s in the each given concentration and the control. Wet leaves were dried under greenhouse conditions. The leaf discs were placed with their upper surface downwards onto a thin layer of 5% water–agar in 9 cm diameter Petri dishes. Petri dishes were covered with Parafilm® and kept in an incubator with the conditions mentioned above. Mortality was counted for 3 days in daily intervals. Experiments were replicated three times. Nymphs were considered dead if body color changed from yellowish to dark brown.

Sublethal effect of insecticides on T. vaporariorum

In this experiment, the LC_{25} value of each insecticide (obtained from lethality tests) was used as sublethal concentration on third-instar whitefly nymphs in the greenhouse. For this aim, the leaves containing the same age third-instar whitefly nymphs were dipped for 30 s in each given concentration or control. Wet leaves were dried under greenhouse conditions. The leaf discs were placed with their upper surface downwards onto a thin layer of 5 % water-agar. Petri dishes were covered with Parafilm® and kept in an incubator with the conditions mentioned above. The nymphs were observed daily. After emerging, 100 surviving females (less than 24 h old) were transferred into leaf cages containing fresh leaves. Adult lifespan and number of eggs laid were counted. To evaluate the sublethal effect of insecticides on the progeny of the treated parasitoids, 100 eggs of the same age from treated nymphs in each sublethal concentration were randomly collected and the length of different developmental stages, the rate of mortality and parameters related to the life table was recorded daily. This experiments recorded until the death of the last adult insect.

Sublethal effects of insecticides on E. formosa

T. vaporariorum were released on green bean, *P. vulgaris* with two clean developed leaves for one day. Then whiteflies were removed, and these plants were maintained at the conditions mentioned above. Adults of *E. formosa* were released on the new third-instar whitefly nymphs for 48 h. When parasitized whitefly nymphs turned black, the healthy green bean leaves with 3-day-old parasitoid pupae dipped in each treatment for 30s, with nine replicates. Wet leaves were dried under greenhouse conditions. The adult emergence in treatments were counted daily. The number of emerged progenies were recorded within 7 days. The number of eggs laid of the surviving female progeny was recorded. One hundred newly emerged females were collected and placed individually in plastic cage, on the green bean leaves with third-instar *T. vaporariorum* nymphs (Gholamzadeh *et al.*, 2012). To evaluate the sublethal effect of insecticides, on the progeny of the treated female, 100 eggs of the same age from treated pupae in each sublethal concentration were collected and the length of different developmental stages, the rate of mortality and parameters related to the life table was recorded daily. These experiments continued until the death of the last insect. Pest biological parameters include gross reproductive rate (*GRR*), the net reproductive rate (R_0), intrinsic rate of increase (r_m), finite rate of increase (λ) and = mean generation time (T) due to their importance in evaluating the effect of sublethal doses on the trend of growth and reproduction and the number of generations, they were examined according to the following parameters.

$$\text{Gross reproductive rate } (GRR) = \sum m_x$$

$$\text{The net reproductive rate } (R_0) = \sum_{x=0}^{\infty} l_x m_x$$

$$\text{Intrinsic rate of increase (rm)} \sum_{x=0}^{\infty} e^{-r(x+1)} l_x m_x = 1$$

$$\text{Finite rate of increase } (\lambda) = e^r$$

$$\text{Mean generation time } (T) = \frac{lnR_0}{r}$$

Statistical analysis

The sublethal concentrations were calculated using the probit analysis in the software SPSS (Ver. 20). Estimation of biological parameters were calculated using age-stage-specific bisexual life table theory (Chi and Liu, 1985). Data analysis was done using the software (Chi, 2022). Also, the standard error and average parameters were calculated. To stable estimates, we used 100,000 bootstraps. The averages obtained from the bootstrap were compared and grouped by the Paired Bootstrap Comparison software. Figures and Box-plots were drawn by the Sigmaplot (Ver. 12.3) software.

RESULTS

Acute toxicity of insecticides to third-instar nymphs of Trialeurodes vaporariorum

The LC_{50} and LC_{25} values, confidence limit (95%) and regression slope, 3 days after treated with emamectin, spinosad and buprofezin concentrations on 3rd instar *T. vaporariorum* nymphs in the greenhouse are shown in (Table I). According to the LC_{50} values, buprofezin was highly toxic and spinosad was least toxic on the 3rd-instar *T. vaporariorum* nymphs.

Sublethal effect of insecticides on the immature stages treated at third-instar nymphs of T. vaporariorum

The effects of LC_{25} value of the insecticides on the egg, nymph, and pupal stages treated at 3rd instar nymphs of *T. vaporariorum* are shown in Table II.

Table I. Lethal effect (LC) of emamectin, spinosad and buprofezin on 3rd instar *T. vaporariorum* nymphs at 3 days after exposure.

Treatments	No.	Slope±SE	X^2 (df)	LC_{25} (mg/l)	LC_{50} (mg/l)
Emamectin	360	2.56±0.70	0.32 (3)	63.13 (40.10-76.16)	115.05 (94.94-179.26)
Spinosad	360	5.88±1.54	0.32 (3)	80.12 (69.09-87.17)	104.06 (95.15-130.10)
Buprofezin	360	3.59±1.36	0.89 (3)	60.20 (26.20-70.10)	93.12 (81.11-156.06)

Table II. Mean (± SE) of developmental time (day) for immature stage of *T. vaporariorum* exposed to sublethal concentrations (LC_{25}) of insecticides and control. Means with similar letters in each row do not have significant differences with each other (Paired bootstrap, $p < 0.05$).

Life stages (day)	Treatment			
	Control	Spinosad	Emamectin	Buprofezin
Egg	6.27±0.07ab	6.38±0.14a	6.44±0.11a	6.09±0.17b
1st-instar nymph	3.80±0.11b	4.07±0.14ab	4.33±0.15a	4.05±0.19ab
2nd-instar nymph	3.28±0.07c	3.65±0.12b	3.50±0.09bc	4.26±0.17a
3rd-instar nymph	2.34±0.08c	3.61±0.23b	2.61±0.09c	4.31±0.32a
Pupa	2.08±0.08c	3.16±0.15b	2.30±0.12c	4.58±0.25a

Table III. Mean (± SE) parameters adult stage of *T. vaporariorum* exposed to sublethal concentrations (LC_{25}) of insecticides and control. Means with similar letters in each row do not have significant differences with each other (Paired bootstrap, $p < 0.05$).

Parameter	Treatment			
	Control	Spinosad	Emamectin	Buprofezin
Female longevity (day)	8.07±07a	4.00±0.14c	8.00±0.14a	4.88±0.49b
APOP (day)	0.34±0.06b	0.34±0.03b	0.34±0.06b	0.80±0.04a
TPOP (day)	18.10±0.06d	22.08±0.29b	19.72±0.23c	25.00±0.55a
Oviposition days (day)	5.28±0.20a	3.88±0.10b	4.97±0.14a	3.84±0.11b
Fecundity (egg/female)	47.93±2.90a	23.46±1.72c	44.76±1.54b	15.04±1.25d
Daily fecundity (eggs/ days)	9.08±0.48a	6.04±0.34b	9.01± 0.33a	3.92±0.22c
Sex ratio (%F)	0.58±0.07a	0.52±0.07b	0.58±0.07a	0.50±1.37b

All treatments significantly prolonged the egg period (F = 34.78; df = 3, 376; $P < 0.001$). The shortest period was related to buprofezin and the longest period was related to emamectin. Insecticides prolonged the duration of the first, second, third instar nymph and pupal stage compared with control (F = 32.47; df = 3, 344; $P < 0.001$), (F = 32.08; df = 3, 328; $P < 0.001$), (F = 33.67; df = 3, 310; $P < 0.001$), (F = 44.16.; df = 3, 298; $P < 0.001$). The longest period of the first instar nymph was related to emamectin. The shortest period of the second instar nymph was related to control and the longest period was observed in buprofezin. The longest duration of the third instar nymph and pupal stage of insects exposed to LC_{25} of insecticides were related to buprofezin (Table II).

Sublethal effect of insecticides on the adults treated at 3rd-instar nymphs of T. vaporariorum

The effects of LC_{25} value of the insecticides on female longevity, APOP (adult pre-oviposition period of female adult), TPOP (total pre-oviposition period of female counted from birth), sex ratio (female%), oviposition days and total fecundity parameters adult stage of *T. vaporariorum* are shown in Table III. Sublethal concentration of the insecticides affected female longevity, oviposition days, APOP, TPOP, fecundity and daily fecundity of *T. vaporariorum* in comparison to control insects (F = 42.22; df = 3, 218; $P < 0.008$), (F = 67.12; df = 3, 218; $P < 0.001$), (F = 34.12; df = 3, 218; $P < 0.001$), (F = 79.32; df = 3, 218; $P < 0.001$), (F = 17.82; df = 3, 218;

Table IV. Life table parameters of *T. vaporariorum* exposed to LC_{25} concentration of different insecticides. Means with similar letters in each column do not have significant differences with each other (Paired bootstrap, p < 0.05).

Treatments	Parameters				
	R_0 (offspring/ individual)	r_m (day^{-1})	λ (day^{-1})	T (day)	GRR (offspring/individual)
Control	27.80±2.69^{a}	0.180±0.01^{a}	1.20±0.02^{a}	20.35±0.24^{c}	36.34±1.02^{b}
Emamectin	25.96±3.24^{a}	0.149±0.01^{b}	1.16±0.02^{b}	21.84±0.32^{c}	38.47±3.42^{b}
Spinosad	12.20±1.88^{b}	0.102±0.01^{c}	1.11±0.01^{c}	24.47±0.37^{b}	45.51±5.30^{a}
Buprofezin	7.52±1.23^{c}	0.072±0.01^{d}	1.07±0.01^{d}	27.85±0.76^{a}	22.15±2.89^{c}

P < 0.001) and (F = 56.32; df = 3, 218; P < 0.001), respectively. The female longevity of adults treated with LC_{25} of spinosad was reduced by 4.00 days. The shortest oviposition days was observed in buprofezin and spinosad. The longest pre-oviposition period of female was observed in buprofezin. Fecundity was also significantly affected by different insecticides. The most fecundity was observed in control and the least eggs were observed in buprofezin. The daily fecundity in buprofezin was reduced under the influence of different insecticides (Table III).

Sublethal effects of insecticides on whitefly life table parameters

The results obtained from the investigation of the net reproduction rate (R_0), Intrinsic rate of increase (r_m), finite rate of increase (λ), the average duration of one generation (T) and the gross reproduction rate (GRR), third instar whitefly nymphs treated with different insecticides is shown in Table III. The highest R_0 of the *T. vaporariorum* were observed in control. The lowest R_0 was observed in buprofezin. The highest r_m and λ were observed in the control. The lowest r_m and λ was observed in buprofezin. The effect of insecticides on the duration of one generation (T) of whitefly was statistically significant. The shortest period was related to control and emamectin, and the longest period was related to buprofezin. The GRR of whitefly was also significantly affected by different insecticides, and the highest value was observed in spinosad and the lowest value was observed in buprofezin (Table IV).

The effect of insecticides on the age-specific survival rate (l_x), age-specific fecundity (l_xm_x) and age-specific fecundity -growth stage (m_x) of T. vaporariorum

Examining the age-specific fecundity curve (l_xm_x) and the age-stage-specific fecundity (m_x) showed that the treatment with insecticides caused adverse effects on the adults of *T. vaporariorum* and delayed the start of oviposition in them compared to the control. Adults that were affected by buprofezin in the egg stage entered the reproduction stage with delay, while the adults that were not affected by the insecticides entered this stage of life faster than other treatments. The highest rate of age-specific fecundity in females (m_x = 9.23) and age-specific fecundity of adult insects (l_xm_x = 7.20) in the control treatment was compared to other insecticides. The lowest age-specific fecundity of adult was in buprofezin treatment (l_xm_x = 1.34) (Fig. 1).

Evaluation of sublethal effects of insecticides on Encarsia formosa

Effect of different insecticides on the immature treated at pupal stage of E. formosa

Development time of the *E. formosa* treated at pupal stage with different insecticides are shown in Table IV. All insecticides significantly affected the duration of the egg-larva period (F = 17.39; df = 3, 340; P < 0.001). The shortest period was related to control and the longest period was related to emamectin and spinosad. There was no significant difference in the development time of pupal stage (F = 12.32; df = 3, 298; P < 0 .321). The effect of different insecticides on the pre-adult stage, it was statistically significant (F = 11.22; df = 4, 298; P < 0.001). The shortest period was related to control and buprofezin (Table V).

Table V. Mean (± SE) of developmental time (day) for immature stage of *Encarsia formosa* exposed to sublethal concentrations(LC_{25}) of insecticides and control. Means with similar letters in each column do not have significant differences with each other (Paired bootstrap, *p*<0.05).

Treatments	Egg- Larva	Pupa	Pre-adult
Control	8.27±0.18^{c}	7.18±0.12^{a}	15.88±0.14^{b}
Emamectin	9.49±0.19^{a}	7.43±0.14^{a}	17.10±0.23^{a}
Spinosad	9.85±0.17^{a}	7.31±0.13^{a}	17.24±0.21^{a}
Buprofezin	8.78±0.14^{b}	7.16±0.13^{a}	16.04±0.17^{b}

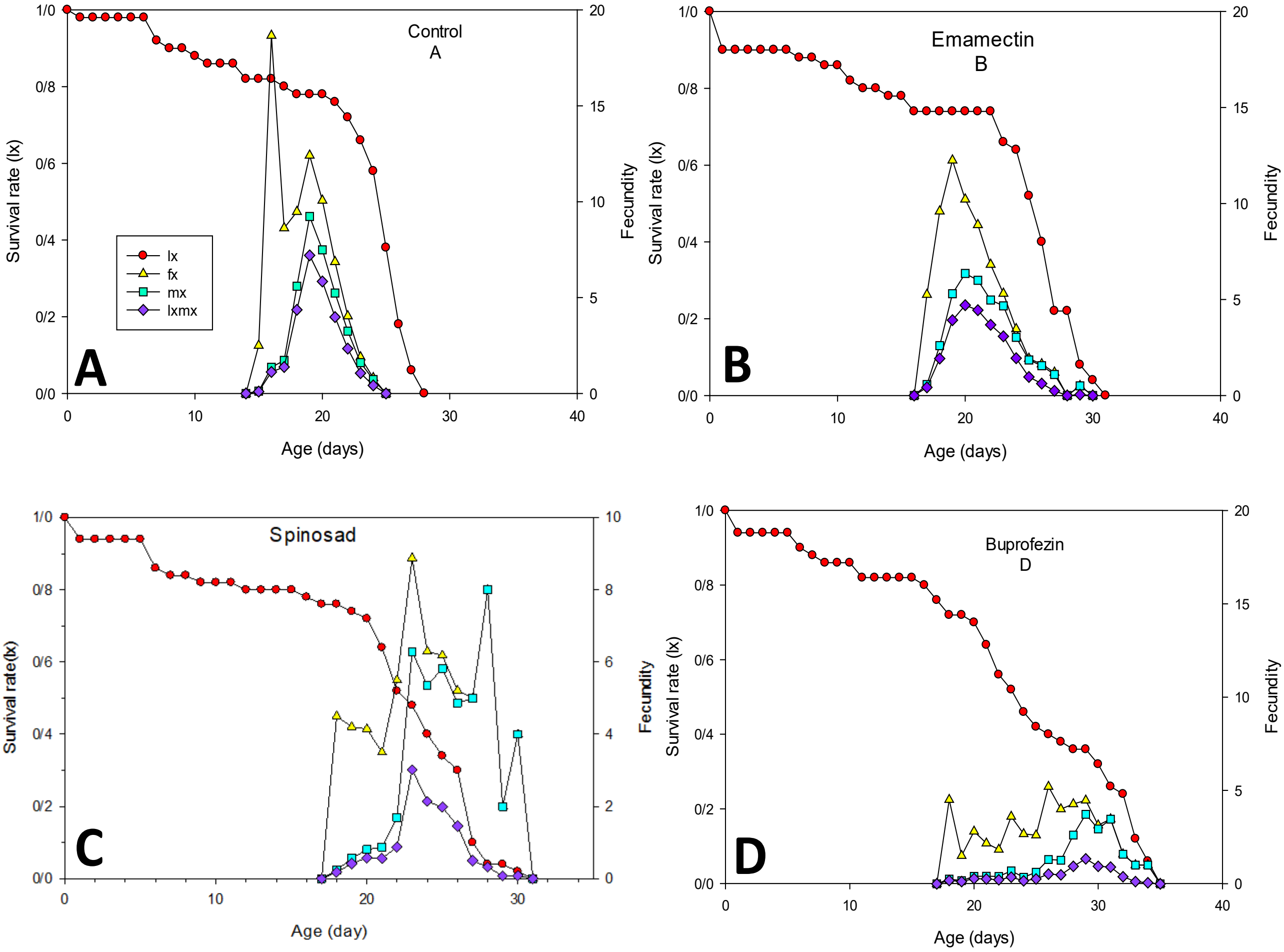

Fig. 1. Age-specific survival rate (l_x), age-specific fecundity (m_x) and age-stage-specific fecundity (l_xm_x) of *Trialeurodes vaporariorum* under the influence of sublethal concentrations (LC_{25}) of emamectin (B), spinosad (C), buprofezin (D) and control (A).

Sublethal effect of insecticides on the adults of Encarsia formosa

LC_{25} values of the insecticides significantly affected on male and female longevity, adult pre-oviposition period of female, total pre-oviposition period of female, oviposition period, total and daily fecundity and sex ratio ($F = 34.32$; df = 3, 67; $P < 0.0001$- Female: $F = 12.19$; df = 3, 174; $P < 0.0001$), ($F = 13.65$; df = 3, 174; $P < 0.121$), ($F = 68.12$; df = 3, 174; $P < 0.001$), ($F = 44.19$; df = 3, 174; $P < 0.001$), (Total fecundity: $F = 77.39$; df = 3, 174; $P < 0.0001$- daily fecundity: $F = 12.30$; df = 3, 174; $P < 0.0001$) and ($F = 98.24$; df = 3, 369; $P < 0.001$), respectively (Table VI). The shortest longevity of male was observed in spinosad. The longest and shortest longevity of female were observed in the control and spinosad. The longest oviposition period was observed in control and buprofezin treatments and the shortest period was observed in emamectin and spinosad. The least fecundity was observed in spinosad. The lowest female was observed in spinosad (Table VI).

Sublethal effect of different insecticides on parameters of the biological table of E. formosa

Different insecticides affected significantly on the net reproduction rate (R_0), Intrinsic rate of increase (r_m), Finite rate of increase (λ), the average duration of one generation (T) and the gross reproduction rate (*GRR*) of *E. formosa*. The highest R_0 of the *E. formosa* was observed in control and buprofezin. The lowest in emamectin was observed. The highest r_m and λ also was observed in control and buprofezin. The shortest period of one generation (T) was related to control and buprofezin and the longest period was related to spinosad and emamectin. Also, the highest *GRR* of *E. formosa* was observed in control and the lowest value was observed in emamectin and spinosad (Table VII).

Table VI. Mean (± SE) parameters adult stage of *Encarsia formosa* exposed to sublethal concentrations (LC_{25}) of insecticides and control. Means with similar letters in each row do not have significant differences with each other (Paired bootstrap, $p < 0.05$).

Parameter	Treatment			
	Control	**Spinosad**	**Emamectin**	**Buprofezin**
Female longevity(day)	7.87±0.15^{a}	7.10±0.12^{b}	6.72±0.13^{c}	7.64±0.15^{a}
Male longevity(day)	6.21±0.27^{a}	5.79±0.26^{b}	5.66±0.44^{b}	6.59±0.76^{a}
APOP (day)	0.37±0.07^{a}	0.39±0.07^{a}	0.35±0.07^{a}	0.34±0.06^{a}
TPOP (day)	16.61±0.22^{b}	18.05±0.29^{a}	18.04±0.27^{a}	16.60±0.27^{b}
Oviposition days (day)	6.41±0.15^{a}	5.73±0.16^{b}	5.43±0.16^{b}	6.25±0.15^{a}
Fecundity (egg/female)	52.11±0.92^{a}	45.85±1.17^{b}	42.04±1.21^{c}	51.21±0.89^{a}
Daily fecundity (eggs/ days)	8.13±0.36^{a}	8.00± 0.37^{a}	7.74±0.36^{b}	8.20±0.37^{a}
Sex ratio (%F)	0.54±0.07^{a}	0.48±0.07^{b}	0.46±0.05^{b}	0.53±0.08^{a}

Table VII. Life table parameters of *Encarsia formosa* treated with sublethal concentration (LC_{25}) of different insecticides and control. Means with similar letters in each column do not have significant differences with each other (Paired bootstrap, $P < 0.05$).

Treatments	Parameters				
	R_0 (offspring/individual)	**r_m (day^{-1})**	**λ (day^{-1})**	**T (day)**	**GRR (offspring/individual)**
Control	28.77±2.64^{a}	0.178±0.01^{a}	1.19±0.01^{a}	18.77±0.24^{b}	45.38±3.54^{a}
Emamectin	18.49±2.36^{c}	0.145±0.01^{b}	1.16±0.01^{b}	20.11±0.26^{a}	33.82±3.28^{c}
Spinosad	19.34±2.17^{b}	0.147±0.01^{b}	1.16±0.01^{b}	20.17±0.27^{a}	34.08±2.82^{c}
Buprofezin	27.24±2.60^{a}	0.174±0.01^{a}	1.19±0.01^{a}	18.86±0.22^{b}	41.18±3.74^{b}

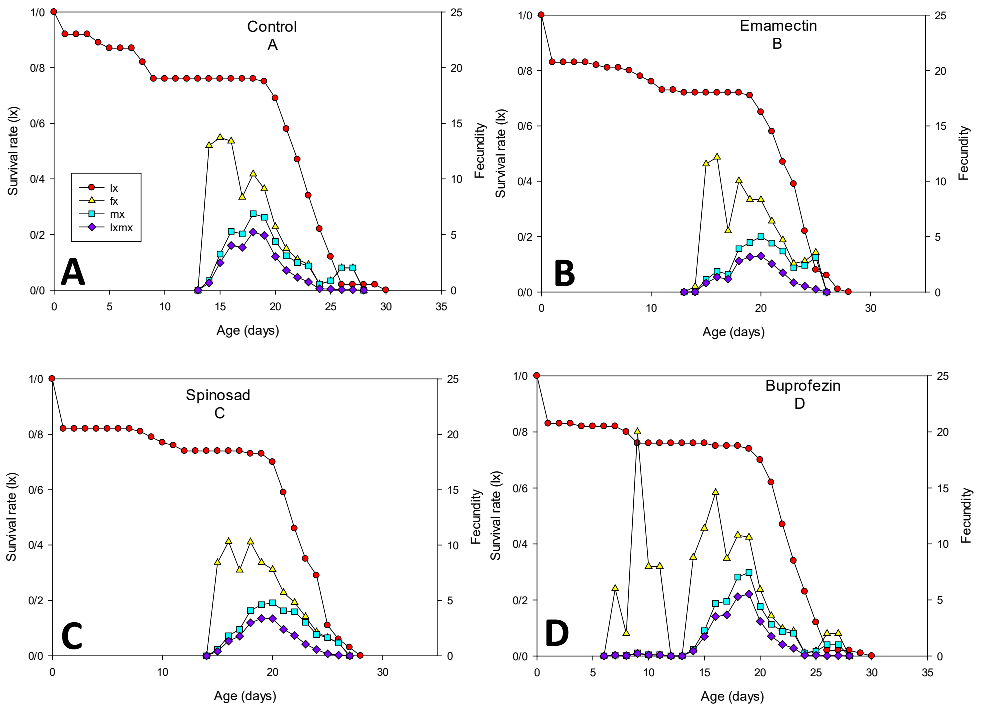

Fig. 2. Age-specific survival rate (l_x), age-specific fecundity (m_x) and age-stage-specific fecundity ($l_x m_x$) of *Encarsia formosa* under the influence of sublethal concentrations (LC_{25}) of emamectin (B), spinosad (C), buprofezin (D) and control (A).

The effect of different insecticides on the age-specific survival rate (l_x), age-specific fecundity (l_xm_x) and age-specific fecundity growth stage (m_x) of Encarsia formosa

The age-specific fecundity curve (l_xm_x) and the age-stage-specific fecundity (m_x) of *E. formosa* (Fig. 2) show that the treatment with sublethal insecticides caused adverse effects on the adults of *E. formosa* and delayed the start of oviposition in them compared to the control (Fig. 2). These curves also show adults that were affected by insecticides, started the reproduction stage with delay, while in control, started this stage of life faster than other treatments. The highest rate of age-specific fecundity in females (m_x = 6.86) and age-specific fecundity of adults (l_xm_x = 4.92) in the control treatment was compared to other insecticides. The lowest age-specific fecundity of adult was in emamectin treatment (l_xm_x = 3.25).

DISCUSSION

Pest damage to food products is still undeniable. The use of chemical compounds is considered as the most common method of controlling pests and plant diseases (Lahlali *et al*., 2022). The use of insecticides with the greatest effect on the pest and the least adverse effect on natural enemies is the concern of most researchers (Janssen and Van Rijn, 2021). The results of this research showed that used insecticides on *T. vaporariorum* had negative effect on duration of immature stages, reproduction, longevity and subsequently the population growth rate of the F_1 generation. So, the most sublethal effects were related to offspring whose parents' third nymphal stage were affected by buprofezin. The lowest net R_0, r_m, λ and the longest duration of one generation (T) were related to buprofezin. Regarding the sublethal effects of the used insecticides, the highest net reproduction rate (R_0), increase (r_m), the increase (λ) and the longest duration of a generation (T) was related to emamectin. In the sublethal effects of the used insecticides on the biological parameters of the parasitoid wasp, *E. formosa*, the lowest net reproduction rate (R_0), the intrinsic rate of population growth (r_m), the finite rate of population increase (λ) and the longest duration of one generation (T) belonged to emamectin. Our results are consistent with Sohrabi *et al.* (2011) that reported the buprofezin significantly decreased stable population and biological parameters of *B. tabaci* while imidacloprid did not have a significant difference with the control in adult longevity and oviposition period. Similarly, Gogi *et al*. (2021) showed that exposure to the residues of buprofezin caused a decrease in oviposition and hatching percentage of whitefly eggs. Similar to our results, Esmaeily *et al*. (2014) showed that buprofezin decreased r_m and λ values of whitefly females. Zhang *et al*. (2023) that reported LC_{25} concentration of emamectin benzoate prolonged larval period of *Spodoptera frugiperda*. A similar increase in duration of larval stages was found in 3rd instar larvae of *H. armigera* that were exposed to LC_{30} values of emamectin benzoate (Parsaeyan *et al*., 2013). Also, Safavi and Bakhshaei (2017) reported that sublethal concentrations of Calypso® reduced the longevity and fecundity of exposed female whiteflies compared to control insects. Moreover, their results indicated that LC_{50} and LC_{30} concentrations adversely influenced the demographic parameters of *T. vaporariorum* compared to control. The intrinsic rate of increase (r_m), as the most important life table parameter, was significantly lower in individuals treated with both concentrations in comparison with r_m of control insects. Other life table parameters (R_0, λ and T) were also significantly lower in treated insects. In our research similar results was observed. Sublethal effects such as reductions in reproductive capacity and longevity of survivors will likely result in negative impacts on insect population dynamics (Xin *et al*., 2019). Few studies have been published on the use of demography and similar measures of the population growth rate for evaluating the effect of chemical insecticides on insects, especially in the context of insect natural enemies (Drobnjaković *et al*., 2017; Nozad-Bonab *et al*., 2021). The sublethal effects of buprofezin, abamectin, and a plant-derived extract on mortality, development time, adult longevity, and fecundity of *E. formosa* were studied by Rashidi and Ganbalani (2018). Development time was decreased following exposure to sublethal concentrations (LC_{30}) of all insecticides. Treatment of larvae and pupae with buprofezin or abamectin significantly reduced the longevity of adults. However, a decrease in fecundity was observed when adult wasps were exposed to abamectin. It is detrimental to the survival, longevity and fertility of *E. formosa* and should be developed for use in integrated pest management of the *T. vaporariorum*, in greenhouse production systems. Abd-Ella (2015) reported that spinetoram and emamectin benzoate were moderately selective between *E. inaron* and the nymphal and adult stages of *Siphoninus phillyreae* (Haliday) (Homoptera: Aleyrodidae), whereas, abamectin had the lowest selectivity. Sublethal effects of imidacloprid on *E. formosa* was performed by Drobnjaković *et al*. (2017). Sublethal effects of pymetrozine on *E. formosa* by Drobnjaković *et al*. (2020). Longevity of wasps exposed for 48 h to residues of the pymetrozine insecticide was shorter than that of control wasps. The instantaneous rate of increase (r_m) of surviving adult wasps was also significantly reduced. Juvenile development of the parasitoid in treated pupae was significantly extended.

Nozad-Bonab *et al*. (2021) studied the lethal and sublethal effects of four chemical insecticides (abamectin, indoxacarb, chlorantraniliprole, and spinosad) on a widespread egg parasitoid, *Trichogramma brassicae* Bezdenko, were estimated. Due to results, the fertility and other life table parameters of the individuals emerging from the treated eggs were estimated. All of the chemical insecticides had harmful effects on *T. brassicae.*

Toxicity of seven biorational insecticides against *Bemisia tabaci* and their selectivity for its parasitoid, *E. formosa* by Gogi *et al*. (2021) was investigated. Due to results buprofezin proved to be efective (66.3-84.2% population-reduction) against *B. tabaci.* Also buprofezin was slightly-harmful biorationals (30–79% mortality) against the respective stages of *E. formosa*. Effect of spirotramate insecticide on life history traits and population growth of *E. formosa* by Drobnjaković and Marčić (2021) significantly reduced life expectancy. Spirotetramat significantly extended juvenile growth (1.0-1.4 days), and significantly reduced longevity (0.7 days) and instantaneous growth rate. Similar our research, in a study by Gholamzadeh *et al*. (2012), it was found that the buprofezin caused 19.87 and 11.87% mortality in adults and pupae, respectively. Buprofezin had no adverse effects on fecundity and longevity of parasitoids. The life table test showed that buprofezin did not has a significant effect on the intrinsic rate of natural increase (r_m). The results of Heidari *et al*. (2015) showed that buprofezin did not affect the longevity and fecundity. Overall, the results show that buprofezin can be used in an integrated pest management program or a biological control program without detrimental effects on the effectiveness of this natural enemy in greenhouses. Considering the sublethal effects on the whitefly and the least effect on the parasitoid *E. formosa*, buprofezin is a suitable choice to control this pest in integrated management programs of this pest.

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IRB approval

The study was approved by the University of Mahabad Branch, Islamic Azad University, Mahabad, Iran.

Ethical statements

The study was approved by the Ethics Committees of the authors' institutions.

Statement of conflict of interest

The authors have declared no conflict of interest.

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