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ORIGINAL ARTICLE

Direct interaction between micronutrients and bell pepper (*Capsicum annum* L.), to affect fitness of *Myzus persicae* (Sulzer)

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Abstract

The green peach aphid, *Myzus persicae* (Sulzer), is a polyphagous and holocyclic aphid which significantly damages agricultural crops. In the current study, the effects of micronutrients on some secondary metabolites of bell pepper (*Capsicum annum* L.) leaves and their subsequent influence on the life table parameters of *M. persicae* were investigated under greenhouse conditions. The flavonoid content in bell pepper leaves significantly changed following micronutrient treatments in the wavelength of 270 nm while there were no significant differences in the wavelengths 300 and 330 nm. The highest anthocyanin content was recorded after Fe treatment (3.811 mg · ml^{-1}) while the total phenolic content in the bell pepper leaves increased after Mn (541.2 mg · ml^{-1}) treatment compared to Fe (254.5 mg · ml^{-1}) and control (216.33 mg · ml^{-1}), respectively. The highest values of intrinsic (r) and finite rates of population increase (λ) of *M. persicae* were gained with Zn (0.320 and 1.377 day^{-1}, respectively) treatment although the highest and the lowest values of the mean generation time (T) were found with Fe and Zn (14.07 and 12.63 days, respectively) treatments, respectively. Our findings suggest that Mn, more than Zn micronutrients, decreased ecological fitness of green peach aphid and may help enhance the efficiency of pest control techniques.

Keywords: life table, micronutrient, *Myzus persicae*, plant-insect interaction, plant metabolite

Introduction

The green peach aphid, *Myzus persicae* (Sulzer), is a polyphagous and holocyclic aphid which significantly damages agricultural crops because it establishes large populations on crops and intensively feeds on all vegetative parts of host plants (Villanueva *et al.* 2014; Özgökce *et al.* 2018). The use of synthetic insecticides is an ordinary strategy to control *M. persicae*, but resistance to several insecticides has been reported around the world (Henry *et al.* 2017). Therefore, alternative control approaches to reduce chemical spraying need to be integrated for effective control (Carlberg *et al.* 2012).

It is believed that micronutrient fertilizers play a critical role in processing macromolecule synthesis, growth hormones, photosynthesis, cell division and nucleic acid metabolism in plants (Hansch and Mendel 2009; Khosa *et al.* 2011; Dehghani-Yakhdani *et al.* 2019). They also enhance plant tolerance versus sap-sucking and chewing insects (Gogi *et al.* 2012). Micronutrients such as iron (Fe), zinc (Zn), manganese (Mn) and copper (Cu) can improve soil fertility, growth and quality of plants, and the amount of defensive chemicals, which in turn can affect eco-physiological features of herbivorous insects (Hansch and Mendel

2009; Lahijie 2012; Mardani-Talaee *et al.* 2016; Dehghani-Yakhdani *et al.* 2019). In sap-sucking insects, the use of Fe decreased the population of brown plant hopper, *Nilaparvata lugens* (Stål) (Hem.: Delphacidae) (Bala *et al.* 2018), the number of laid eggs and population growth of pistachio psyllid, *Agonoscena pistaciae* Burckhardt and Lauterer (Hem.: Aphalaridae) (Dehghani-Yakhdani *et al.* 2019). Conversely, zinc treated plants can significantly increase the population of sap-sucking *M. persicae* (Mardani-Talaee *et al.* 2016, 2017), but it had negative effects on the survival and the development of *N. lugens* (Bala *et al.* 2018).

It has been claimed that the nutritional quality of plants is important in insect-plant interactions because plants grown in high quality medium may develop resistance to phytophagous insects (Bennett and Wallsgrove 1994; Zarghami *et al.* 2010; Shah 2017; Bala *et al.* 2018). Moreover, allelochemical compounds in plants, which are produced in response to biotic and abiotic stresses, have an important influence on the nourishment and development of polyphagous insects (Bernays and Chapman 1994; Schoonhoven *et al.* 2005; Iason *et al.* 2012; Wang *et al.* 2013). In fact, mineral nutrients and allelochemical compounds of host plants can induce resistance against insects and can potentially be critical defensive tools for pest management (Cakmak 2005; Amtmann *et al.* 2008; Romheld and Kirkby 2010; Marschner 2012; War *et al.* 2012). The aim of the current study was to determine if bell pepper plants treated with four types of micronutrients viz. Fe, Zn, Mn and Cu influence the contents of some secondary metabolites and the life table traits of *M. persicae* under greenhouse conditions.

Materials and Methods

Plant and aphid

The seeds of California Wonder var. bell pepper were cultivated in plastic vials (5 l, with 12.5 cm diameter and 20 cm height) filled with 2 : 1 soil and sand in a greenhouse [at 25 ± 5°C, 60 ± 10% relative humidity (RH) and 14 : 10 h (L : D) photoperiod]. The soil for growing plants was provided from the campus of the Faculty of Agriculture at Lorestan University and an analysis was done on soil samples (Table 1).

A colony of *M. persicae* was obtained from the laboratory of entomology at the University of Mohaghegh Ardabili, Ardabil, Iran. The aphids were transferred to plants raised in a greenhouse. To maintain the aphid colony, aphids were transferred daily from infested pots to un-infested new ones. Before the experiments, the aphids were reared for two generations on bell peppers (cv. California Wonder) to gain a homogenous cohort.

Table 1. Some main physicochemical properties of farm soil used for the research

Soil property	Value
pH	7.43
Electrical conductivity (EC)	0.481 deci Siemens/meter
N (nitrogen)	0.140%
Ca (calcium)	1.23%
K (potassium)	0.02%
P (phosporus)	5.3 mg · kg^{-1}
Na (sodium)	0.036%
Mg (magnesium)	0.062%
Cu (copper)	0%
Zn (zinc)	0%

Micronutrient treatments

The iron micronutrient (Alpha Fe) was purchased from the Mazrae Faraze Aseman Company in Tehran, Iran. Zinc ($ZnSO_4$; Biomin Zinc L; glycine chelated zinc), manganese ($MnSO_4$; Biomin Manganese-L; glycine chelated manganese), and copper ($CuSO_4$; Biomin Copper-L; glycine chelated copper) were purchased from the Bazargan Kala Company in Tehran, Iran. Plants at four- to six-expanded leaf stage were treated with the following treatments; foliar application of aqueous Fe (13%) at 1.7 g · l^{-1}, Zn (7%), Mg (5%) and Cu (4%) at 1 m · l^{-1}. Bell pepper plants sprayed with water alone were considered as control. Foliage application was performed using a knapsack sprayer with constant pressure (1.5 bar), flat fan nozzles and with a mean droplet size of less than 100 µm. The experiments were done in a completely randomized design with 50 replications per treatment.

Allelochemical compounds in bell pepper leaves

To investigate the secondary metabolite content of the bell pepper leaves before and after aphid infestation, different parts of the plant, treated at eight- to 10-leaf stage were randomly used for flavonoid, anthocyanin and total phenolic analysis. The experiment examined un-infested and infested plants with four replications per treatments. In the aphid infested plants, one adult insect was released per plant, then four plants were collected for allelochemical analyses after 72 h.

Flavonoid and anthocyanin contents

The method of Kim *et al.* (2003) was used to assay flavonoid and anthocyanin contents in the control and mineral treated leaves. Briefly, leaves of bell pepper (0.2 g) from control and treatments were randomly selected and homogenized in 3 ml of acidified ethanol solution (1 : 100 acid acetic : ethanol) before centrifugation at 12,000× g for 15 min. The supernatants were filtered (filter paper Whatman No. 1) and incubated for 5 min in a warm bath (80°C). A 1 l of the reaction mixture was spectrophotometrically monitored at 270, 300 and 330 nm. A similar procedure was also used to measure the anthocyanin while the reaction mixture was incubated in light for 24 h at room temperature. The absorbance was then obtained at 550 nm.

Total phenolic components

According to the method of Slinkard and Singleton (1997), the contents of phenolic components in the pepper plant were assayed by adding 10 ml of 80% methanol in 1 g of fresh samples of bell pepper leaves. The samples were filtered (Whatman No. 1) and the extract was centrifuged at 1000× g for 5 min. Then 100 µl of sample, with 1.5 l of Folin-Ciocalteau (1 : 10) and 1.4 l sodium carbonate (7%) were incubated for 5 min at 35°C. Finally, the absorbance was read at 765 nm.

Investigation of *Myzus persicae* fitness

About 30 plots of Bell pepper plants per mineral treatment at 8–10 leaf stage (ca. 7–10 days after mineral application) were individualized in clip-cages (6 cm dia × 1 cm high) and exposed to >50 adult aphids which were randomly selected from a rearing colony on bell pepper leaves under greenhouse conditions. After 24 h, only one newly hatched nymph was kept in each cage, totaling 50 replications per treatment. The duration of the nymphal stage was daily recorded at 24 h intervals. After the emergence of adults, their fecundity was recorded by counting the number of nymphs. The duration of nymphal development was daily evaluated until death of all adults (Mardani-Talaee *et al.* 2016).

The data were calculated based on the age-stage, two-sex life table (Chi and Liu 1985; Chi 2018). The age-specific (S_{xj}) and survival rate (l_x) were calculated as:

$$S_{xj} = \frac{n_{xj}}{n_{01}}, \qquad l_x = \sum_{j=1}^{k} S_{xj},$$

where: n_{xj} – the number of nymphs and/or adults living to age x and step j, n_{01} – the total number of nymphs in the beginning of the experiment, and k – the number of biological steps.

The formulas age-specific fecundity (m_x) and age-stage specific fecundity (f_{xj}) were calculated as:

$$m_x = \frac{\sum_{j=1}^{k} S_{xj} f_{xj}}{\sum_{j=1}^{k} S_{xj}}, \qquad f_{xj} = \frac{E_{xj}}{n_{xj}},$$

where: k – the number of steps, m_x – daily number of eggs produced per females, S_{xj} – the possibility that neonatal larvae will survival to age x and step j, f_{xj} – the average fecundity of adults of age x and step j, E_{xj} – the total of nymphs and n_{xj} – the total of adults.

The formula of the population functions such as the gross (GRR) and net (R_0) reproductive rates were calculated as:

$$GRR = \sum_{x=\alpha}^{\beta} m_x, \qquad R_0 = \sum_{x=0}^{\infty} l_x m_x,$$

where: m_x – daily number of eggs produced per females and l_x – survival rate.

The intrinsic (r) and finite (λ) rates of population increase were calculated as:

$$\sum_{x=0}^{\infty} e^{-r(x+1)} l_x m_x = 1, \qquad \lambda = e^r,$$

where: $l_x m_x$ – the age-specific net maternity.

The mean generation time (T) is the time length it takes to enhance a population to R_0 fold at stable age-stage distribution and was calculated as:

$$T = \frac{\ln R_0}{r},$$

where: r – intrinsic rate of population.

Statistical analysis

Normality of the data was confirmed via the Kolmogorov-Smirnov method. The data of allelochemical compounds were analyzed via one-way analysis of variance (ANOVA), followed by a comparison of the means with Tukey's *post hoc* Honestly Significant Difference (HSD) test at $\alpha = 0.05$ with software MINITAB (Ver. 16.0). The life table parameters were investigated according to the theory of the age-stage, two-sex life table and mean comparisons were performed with paired bootstrap test based on confidence interval (CI) of differences via statistical software TWOSEX-MS Chart (Chi 2018). The bootstrap method was used with 100,000 repetitions for each treatment (Akca *et al.* 2015; Saska *et al.* 2016). The figures were designed via means of statistical software Sigma plot (Ver. 12.5).

Results

Allelochemical compounds in un-infested bell pepper leaves

Bell peppers treated with the different micronutrients had no differences in flavonoid content in comparison with control plants at 270 nm (Table 2), but higher contents of flavonoids were recorded at

300 and 330 nm in Fe and Cu treatments (2.189 and 2.015 mg · ml^{-1}, respectively). The lowest flavonoid contents were recorded in Mn treated plants (0.606 mg · ml^{-1}) at 300 nm. The flavonoid contents increased in Fe (2.356 mg · ml^{-1}) treatment but decreased in Cu (1.098 mg · ml^{-1}) treatment at 330 nm (Table 2).

Treatment with Fe significantly increased the anthocyanin content (2.705 mg · ml^{-1}) in the un-infested bell pepper, whereas Zn and Cu treated plants had lower contents of anthocyanin (0.614 and 0.674 mg · ml^{-1}, respectively). The total phenol content significantly increased in plants treated with Fe and Zn (401.4 and 375.5 mg · ml^{-1}, respectively) and decreased in those with Cu (189.8 mg · ml^{-1}) (Table 2).

Allelochemical compounds in infested bell pepper leaves

Zinc treated bell peppers had significantly increased flavonoid content (3.575 mg · ml^{-1}) in infested leaves compared to control (2.394 mg · ml^{-1}) at 270 nm (Table 2), whereas Cu, Fe, Mn, and Zn treatments showed similar amounts of flavonoids at 300 and 330 nm (Table 3). Treatment with micronutrients significantly influenced the amount of anthocyanin and was higher in Fe treated plants (3.81 mg · ml^{-1}) than in those treated with Zn (0.878 mg · ml^{-1}) and Mn, (1.432 mg · ml^{-1}). The content of total phenolic compounds significantly increased in Mn (541.2 mg · ml^{-1}) compared to control (254.5 mg · ml^{-1}) and Fe treated plants (216.33 mg · ml^{-1}) (Table 3).

Effect of micronutrient treatments on the population of *Myzus persicae*

The gross reproductive rate (*GRR*) of the aphids reared on plants treated with Mn decreased in comparison with the control. The net reproductive rate (R_0) decreased in Mn and Cu treated plants in comparison to the control and Fe treatment (Table 4). Micronutrient

Table 2. The effect of various micronutrients on some allelochemical compounds in uninfested bell pepper under greenhouse conditions [25 ± 5°C, 60 ± 10% RH, and 14 : 10 h (L : D)]

Treatments	Flavonoids			Anthocyanin 550 nm	Total phenol 765 nm
	270 nm	300 nm	330 nm		
Control	2.038 ± 0.458 a	1.515 ± 0.211 ab	1.583 ± 0.221 ab	1.083 ± 0.267 ab	246.96 ± 05.56 bc
Mn	1.030 ± 0.234 a	0.606 ± 0.037 b	1.098 ± 0.115 b	1.060 ± 0.044 ab	295.40 ± 08.53 b
Fe	1.659 ± 0.081 a	2.189 ± 0.552 a	2.356 ± 0.507 a	2.705 ± 0.841 a	401.40 ± 13.00 a
Cu	1.735 ± 0.328 a	2.015 ± 0.264 a	1.992 ± 0.107 ab	0.674 ± 0.112 b	189.88 ± 04.48 c
Zn	1.079 ± 0.194 a	1.083 ± 0.064 ab	1.409 ± 0.175 ab	0.614 ± 0.108 b	357.50 ± 24.20 a
df	4, 19	4, 19	4, 19	4, 19	4, 19
F	2.30	5.04	3.38	4.53	40.49
p-value	0.106	<0.05	<0.05	<0.05	<0.05

In each column, differences among treatments were determined via Tukey's test (HSD); means followed by different letters are significantly different ($p < 0.05$)

Table 3. The effect of various micronutrients on some allelochemical compounds in infested bell pepper under greenhouse conditions [25 ± 5°C, 60 ± 10% RH, and 14 : 10 h (L : D)]

Treatments	Flavonoids			Anthocyanin 550 nm	Total phenol 765 nm
	270 nm	300 nm	330 nm		
Control	2.394 ± 0.157 c	2.076 ± 0.193 a	2.068 ± 0.164 a	2.689 ± 0.406 ab	254.56 ± 7.66 c
Mn	2.833 ± 0.278 bc	2.167 ± 0.333 a	2.106 ± 0.309 a	1.432 ± 0.209 b	541.23 ± 42.70 a
Fe	3.507 ± 0.079 ab	2.985 ± 0.137 a	2.864 ± 0.131 a	3.810 ± 1.030 a	216.33 ± 7.57 c
Cu	3.348 ± 0.151 ab	2.902 ± 0.226 a	2.705 ± 0.187 a	2.129 ± .0.347 ab	270.08 ± 21.50 bc
Zn	3.575 ± 0.098 a	2.863 ± 0.075 a	2.863 ± 0.068 a	0.878 ± 0.084 b	368.63 ± 17.40 b
df	4,19	4,19	4,19	4,19	4,19
F	9.02	4.31	4.51	4.60	31.55
p-value	<0.05	0.016	0.014	<0.05	<0.05

In each column, differences among allelochemical compounds were determined via Tukey's test (HSD); means followed by different letters are significantly different ($p < 0.05$)

Table 4. The effect of various micronutrients on the mean (±SE) population growth parameters of *Myzus persicae* under greenhouse conditions [25 ± 5°C, 60 ± 10% RH and 14 : 10 h (L : D)]

Treatments	Sample size (*n*)	*GRR* (offspring)	R_0 (offspring)	*r* (day^{-1})	λ (day^{-1})	*T* (day)
Control	(48)50	127.33 ± 16.90 a	60.82 ± 4.593 a	0.300 ± 0.006 b	1.350 ± 0.008 b	13.67 ± 0.32 ab
Mn	(46)50	82.37 ± 4.859 b	44.92 ± 4.339 b	0.286 ± 0.006 b	1.332 ± 0.008 b	13.26 ± 0.23 bc
Fe	(45)50	93.80 ± 5.198 ab	58.94 ± 4.576 a	0.289 ± 0.007 b	1.336 ± 0.009 b	14.07 ± 0.27 a
Cu	(43)50	90.96 ± 12.04 ab	46.32 ± 4.271 b	0.291 ± 0.008 b	1.337 ± 0.011 b	13.17 ± 0.27 bc
Zn	(48)50	99.18 ± 8.514 ab	57.22 ± 4.685 ab	0.320 ± 0.005 a	1.377 ± 0.007 a	12.63 ± 0.23 bc
df	–	4, 245	4, 245	4, 245	4, 245	4, 245
F	–	123.82	137.19	199.53	208.128	202.3
p-value	–	<0.05	<0.05	<0.05	<0.05	<0.05

GRR – the gross reproductive rate; R_0 – the net reproductive rate; *r* – intrinsic rate of increase; λ – finite rate of increase and *T* – mean generation time. The standard errors were estimated via 100,000 bootstraps and compared through paired bootstrap test based on confidence intervals of differences

fertilizers also had a significant effect on the intrinsic (*r*) and the finite rates of population increase (λ) of the aphids mainly treated with Zn which showed the highest values (Table 4). The mean generation time (*T*) increased in Fe treated bell pepper in comparison with Zn treatment (Table 4).

The fitness of *Myzus persicae* assay; life table parameters

The life expectancies (e_x) of *M. persicae* in the nymphal stage were 23.72, 23.70, 21.32, 21.10 and 19.54 days in the control, Fe, Zn, Cu and Mn, respectively (Fig. 1). The e_x of adult stages was 21.45, 20.14, 19.86, 18.00 and 15.84 days in Fe, the control, Cu, Zn and Mn, respectively (Fig. 1). Mn-treated plants had decreased the e_x for both nymphs and adults of green peach aphid (Fig. 1). The maximum age-stage specific survival rate (S_{xj}) of aphid per female (0.96 %) was observed in untreated (control) and Zn treated – at 10 and 9 days than (0.86 %) than in Cu-treated plants at 9 days (Fig. 2).

The peaks of adult survival rate (l_x) were documented at 0.96, 0.96, 0.96, 0.98 and 0.98 in the plants treated with Cu, Fe, control, Mn and Zn, respectively. The death trend of the last aphid female in the five treatments occurred at 36, 40, 40, 42 and 46 days in Mn, Cu, Zn, Fe and control, respectively (Fig. 3). The first reproduction of *M. persicae* began on the 6th day in Fe, Cu and Zn treated plants and on the 7th day in Mn and control. The peaks of daily fecundity (m_x) were 6.33, 5.36, 5.17, 4.54 and 4.51 nymphs at days 38, 11, 16, 11 and 12 in control, Zn, Fe, Cu and Mn, respectively (Fig. 3). The peaks of the average fecundity of adults of age *x* (f_x) were 6.33, 5.36, 5.17, 4.54 and 4.51 nymphs at days 38, 11, 16, 11 and 12 in control, Zn, Fe, Cu and Mn, respectively (Fig. 3) and the values of the of daily fecundity (m_x) and the average fecundity of adults of age *x* (f_x) were overlapped. The age-specific net maternity ($l_x m_x$) values were 4.94, 4.28, 4.14, 3.82 and 3.42 at days 11, 15, 16, 11 and 11 in plants treated with Zn, control, Fe, Cu and Mn, respectively (Fig. 3).

Discussion

Nowadays, most consumers want healthy food and a decrease in the consumption of chemical pesticides. For this purpose, foliar application of micronutrients can improve the nutritional quality and growth of host plants leading to changes in the fitness of herbivores. Our findings show that micronutrients significantly affected the contents of some secondary metabolites in bell pepper and the life table parameters of *M. persicae*. Plants have antibiosis by using toxins, anti-feeding, and secondary metabolite components against herbivores (Samraj and David 1988; Smith 2005), and also impact the fitness of pest insects (Hesler and Dashiell 2011; Sulistyo and Inayati 2016).

The values of R_0 and *GRR* of *M. persicae* fed Mn-treated plants decreased due to the higher amounts of phenolic compounds versus the control. Manganese is a micronutrient that acts as a cofactor and participates in enzyme activities, lipid and fatty acid metabolism, and photosynthesis (Burnell 1988; Marschner 2002). Thus, Mn contributes to the production of secondary metabolites in plants, such as lignin, flavonoids and indole acetic acid activating many enzymes in the shikimic pathway, which may induce resistance of bell pepper to *M. persicae* (Burnell 1988; Hughes and Williams 1988).

The host plant and availability, some very important bottom-up items, affected the top-down factors i.e., herbivores, predators and parasitoids (Alizamani *et al.* 2017) by affecting their development time, survival,

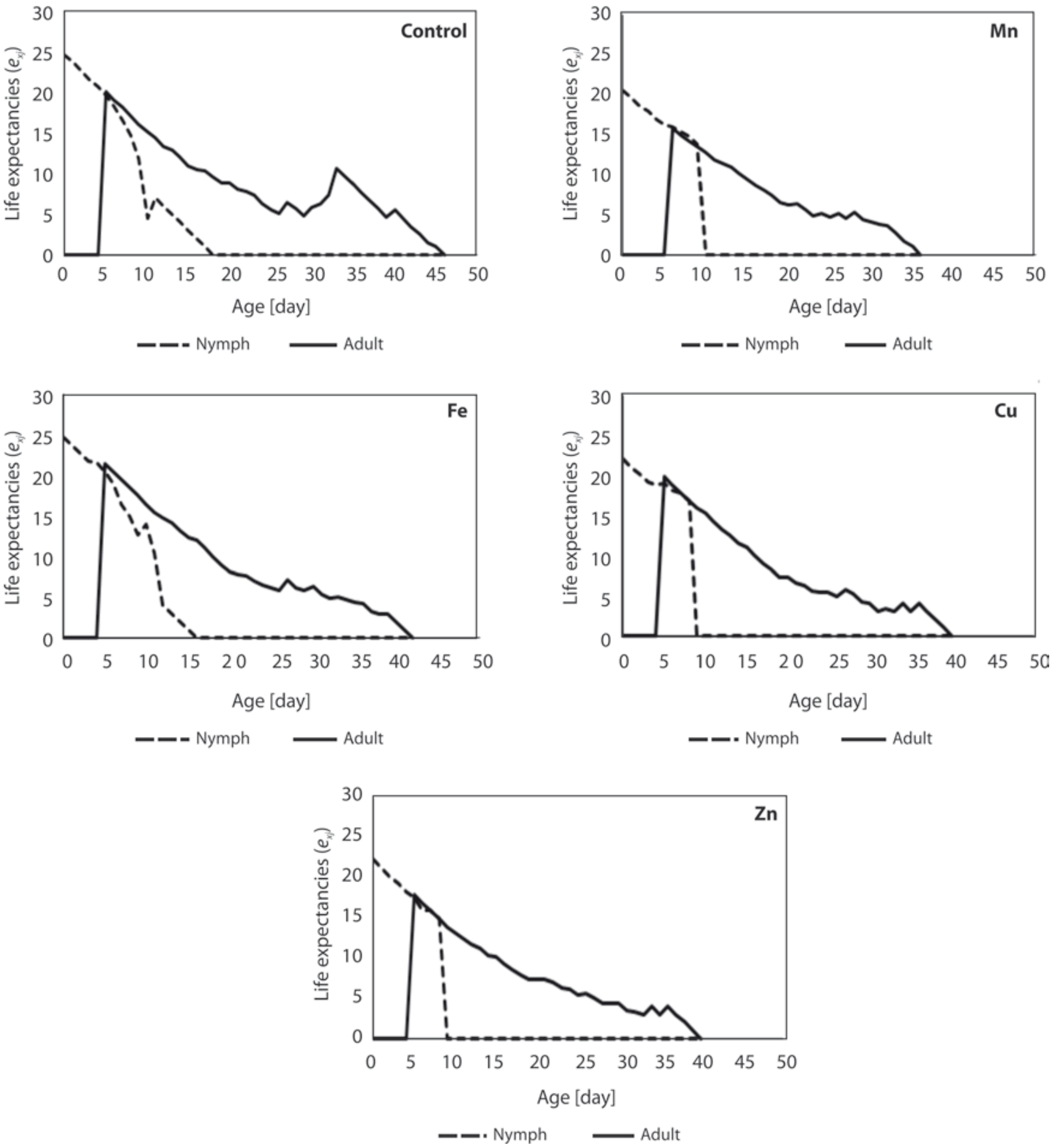

Fig. 1. The age-stage life expectancies (e_{xj}) of *Myzus persicae* reared on different micronutrient fertilizers under greenhouse conditions

fecundity and population parameters (Razmjou *et al.* 2011). On the other hand, food quality is one of the most significant factors that may affect population dynamics of insects (Zarghami *et al.* 2010; Shah 2017). The *r* is a proper index to evaluate pest performance which makes it possible to evaluate other factors such as survival, fecundity and generation time (Southwood and Henderson 2000), development rate and longevity (Dixon 1987). In this study, the highest values of the intrinsic and finite rates of population increase in *M. persicae* were found on Zn-treated plants whereas *r* and λ are the most important population parameters to approach a stable age-stage distribution. Our results indicated the fitness of *M. persicae* reared on Zn-treated bell pepper due to nutrient balance, absorbance, and lack of feeding inhibition. On the other hand, Zn is a micronutrient that plays a key role in many metabolic pathways of plants (Stoyanova and Doncheva 2002; Zayed *et al.* 2011). Zinc has been reported to activate enzymes involved in synthesis of proteins and carbohydrates, cell division, metabolism of nucleic acid, lipid, DNA and RNA, as well as DNA replication, transcription and regulation of gene expression (Coleman 1992; Vallee and Falchuk 1993; Iqbal *et al.* 2000; Stoyanova and Doncheva 2002). Hence, changing the nutritional qualities of host plants via adding Zn fertilizer increased the performance of *M. persicae*. Our results were similar to previous findings of Mardani-Talaee *et al.* (2016).

The life expectancy curve (e_x) and age-specific survival rates (l_x) of *M. persicae* showed similar trends with all of the various micronutrient treatments. The

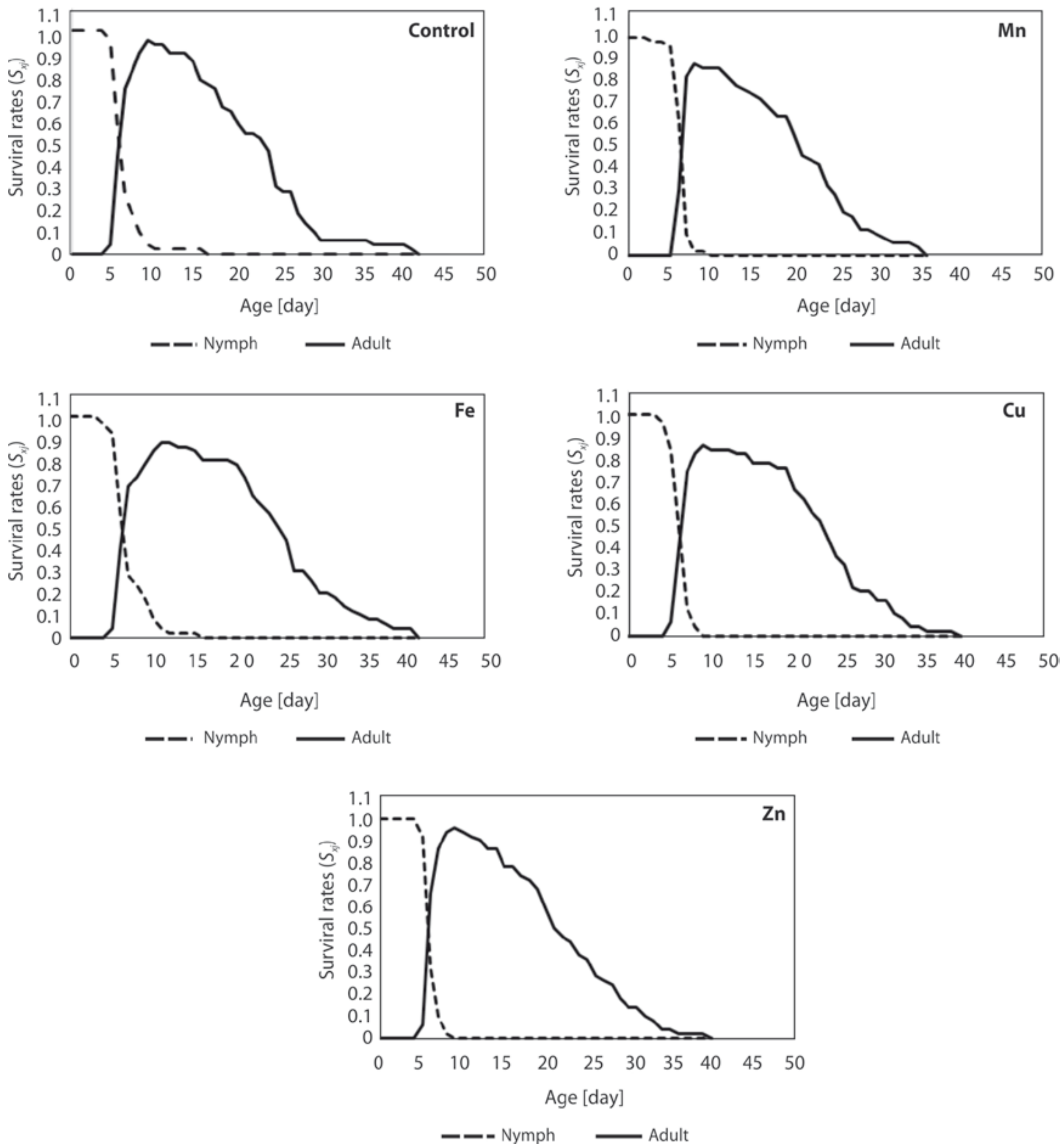

Fig. 2. The effect of different micronutrients on the age-stage specific survival rates (S_{xj}) of *Myzus persicae* under greenhouse conditions

highest survival and life expectancies occurred during the first nymphal period, then decreased gradually until the death of the last female. In this regard, the results of our study are similar to Mardani-Talaee *et al.* (2016, 2017) who reported that *M. persicae* on bell pepper may be due to the presence of secondary plant compounds. Also, the least values of age-specific fecundity (f_{xj}) and age-specific fertility (m_x) of *M. persicae* on different micronutrients were obtained in Mn treated aphids while the highest values were recorded with Zn treatment. Plants respond through different physiological, morphological, molecular and biochemical defense systems to biotic stress such as herbivores and pathogens (Hartmann 2004). In biochemical defense systems, plants produce secondary metabolites that affect feeding, growth and survival of herbivores (Fragoyiannis *et al.* 2001). Secondary metabolites are groups of defense components such as phenolics, alkaloids, terpenoids, and derivative glycosides that increase after exposure to pathogens and/or herbivorous insects (Fragoyiannis *et al.* 2001; Goyal *et al.* 2012). Phenolic compounds are a wide range of aromatic ring materials that produce via the phenylalanine and shikimate enzymes in the shikimic acid pathway within cytoplasm, mainly endoplasmic reticulum (Tsai *et al.* 2006; Bernards and Bastrup-Spohr 2008). The results here show that micronutrients may affect some secondary metabolites in bell pepper leaves. The amount of phenol increases in *M. persicae* infested bell pepper leaves treated with Mn. The decreased feeding performance, fecundity and growth rates as well as life table parameters in sap-sucking insects have been associated with high amounts of phenolic compounds in host plants (Leszczynski *et al.*

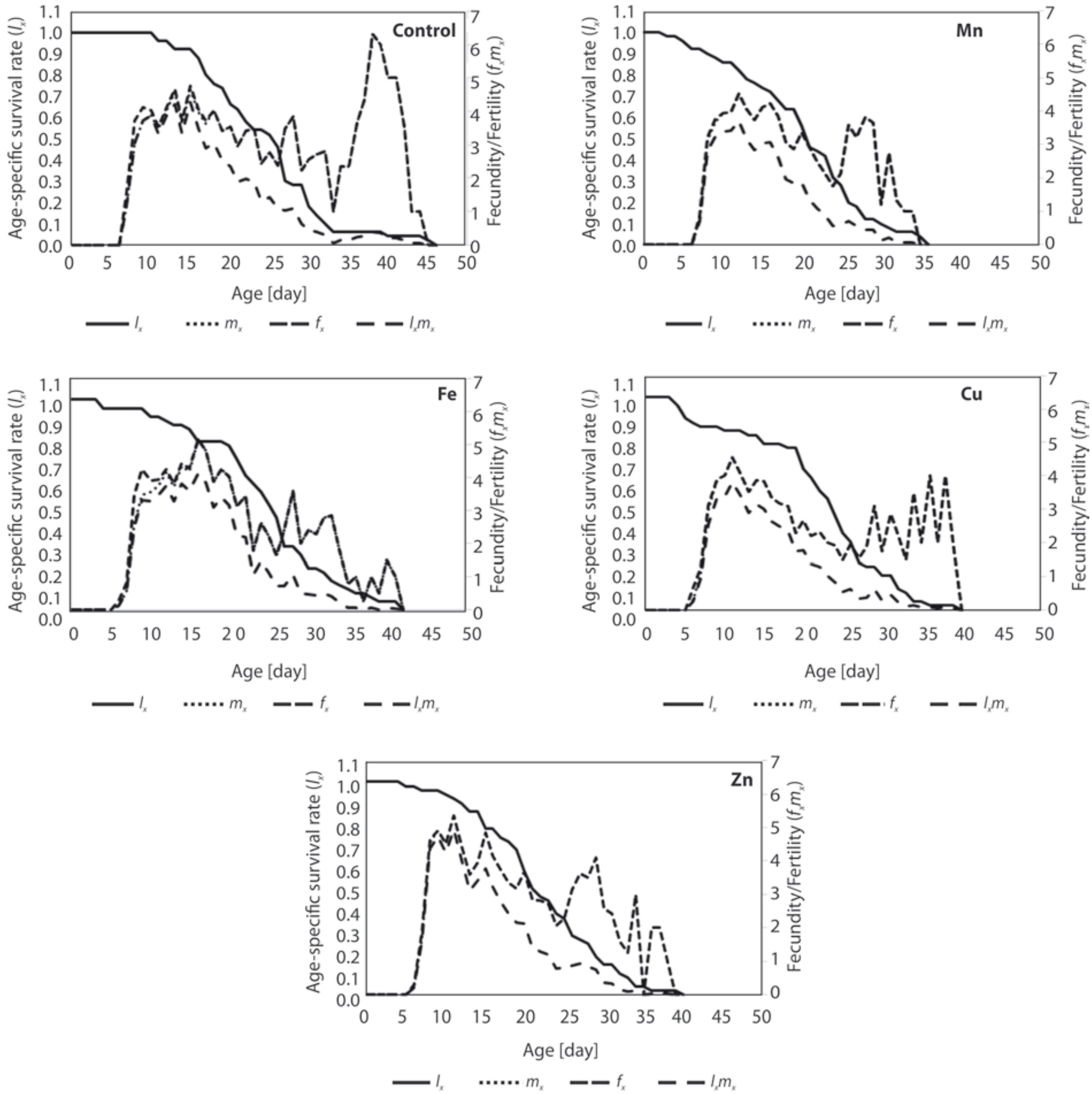

Fig. 3. The effect of different micronutrients on survival rate (l_x), age-stage specific fecundity (f_x), age-specific fecundity (m_x) and age-specific fertility ($l_x m_x$) of *Myzus persicae* under greenhouse conditions

1985; Edwards *et al*. 2009; Mardani-Talaee *et al*. 2016). Thus, phenolic compounds in host plants have anti-feeding properties and may reduce the intrinsic rate of population increase. According to the results obtained in this research, life table parameters of *M. persicae* decreased in plants sprayed with micronutrient fertilizers compared to Zn treated plant.

The amounts of phenolic compounds in Mn treated leaves were significantly higher than other treatments. The foliar application of micronutrient fertilizers helps enhance damaged crops and improve growth (Khan *et al*. 2015). In general, the use of micro- and macro-fertilizers may have several effects on insect growth, survival, fecundity and/or population. In this research, Zn-treated bell pepper improved insect fitness of aphid, although the amount of phenol levels initially increased in the healthy (uninfected) plants and then decreased in the aphid infected leaves. Therefore, it can be inferred that the aphid was initially able to overcome the high phenol contents in un-infected plants through detoxifying enzymes and adapted themselves to the conditions, leading to an increase in its population due to the decrease of phenol content in infested leaves. So, direct interaction between insect-host plants involve complicated adaptations to different defense mechanisms of plants (Francis *et al*. 2006). Finally, Cu, Mn, and Fe improve nutrient balance, plant growth, and may induce resistance in plants against phloem feeding aphids. Subsequently, the ability of green peach aphids to exploit a wide range of plants for feeding and forming colonies can be related to physiological and enzymatic mechanisms that require further study.

Conclusions

In summary, life table parameters of *M. persicae* and the secondary metabolite content of bell pepper treated with micronutrients were examined. Spring bell pepper treated with Mn, more than Zn increased the phenolic levels in plant leaves and as a result decreased the ecological fitness of green peach aphids. Also, foliar application of micronutrients leads to easy and quick absorbance of nutrients through the penetration of stomata or leaf cuticle and entering the cells (Wojtkowiak *et al.* 2016). Thus, these finding can be useful to induce resistance in bell pepper against aphid in the form of integrated pest management (IPM). Further field studies are needed to determine how aphids respond to these bottom up forces and to develop recommendations for other, improved control-based IPM of *M. persicae* in bell peppers and other solanaceous crops.

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