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Biological responses of *Tetranychus urticae* (Acari: Tetranychidae) to sub-lethal concentrations of the entomopathogenic fungus *Beauveria bassiana*

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Research Paper

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Abstract

Tetranychus urticae (Acari: Tetranychidae) is one of the most important pests of agricultural crops with worldwide distribution causing considerable damage to different products. Application of chemical acaricides is one of the most important strategies used for the control of this pest. Entomopathogenic fungi, however, have been proposed as alternative control agents. In this study, sub-lethal effects ($LC_{10} = 6.76 \times 10^2$, $LC_{20} = 8.74 \times 10^3$, and $LC_{30} = 55.38 \times 10^3$ conidia ml^{-1}) of *Beauveria bassiana* strain TV on the life table parameters of *T. urticae* were evaluated under laboratory conditions. The results demonstrated that by increasing the concentration, a significant decline was observed in adult longevity of both male and female individuals. Total fecundity of *T. urticae* was calculated as 45.16, 36.28, 23.98, and 18.21 eggs in control, LC_{10}, LC_{20}, and LC_{30} treatments, respectively. Sub-lethal concentrations drastically affected the population parameters of this mite pest. The intrinsic rate of increase (r) ranged from 0.1983 to 0.1688 day^{-1} for the mites treated with distilled water and LC_{20} treatments, respectively. The net reproductive rate (R_0) was affected by the sub-lethal concentrations (lower value at LC_{30} concentration: 11.19 offspring/individual). Considering the detrimental effects of *B. bassiana* on some biological parameters of *T. urticae*, it can be concluded that this product can be used to develop targeted interventions aimed at integrated pest management of this pest.

Introduction

The two-spotted spider mite, *Tetranychus urticae* Koch (Acari: Tetranychidae), is one of the most destructive mite pests with worldwide distribution (Migeon and Dorkeld, 2006–2017) on different crops such as maize, soybean, cotton, bean, eggplant, tomato, cucumber, potato, strawberry, currants (Sedaratian *et al.*, 2009, 2011; van Leeuwen *et al.*, 2010; Khanamani *et al.*, 2013; Maleknia *et al.*, 2016; Mollaloo *et al.*, 2017; Azadi-Qoort *et al.*, 2019). Direct feeding of *T. urticae* causes a loss of leaf chlorophyll content reducing the net photosynthetic rate, resulting yield losses and finally decline and death of the host plants (Tomczyk and Kropczynska, 1985; Campbell *et al.*, 1990; Park and Lee, 2002; Meck *et al.*, 2012, 2013; Abou El-Ela, 2014).

Applications of synthetic acaricides are noted as the most important strategy for combating the population of this pest (Chen *et al.*, 2019). Unfortunately, high reliance on these chemicals leads to some undesirable consequences such as pest resurgence, development of resistance, environmental pollutions, and negative effects on non-target organisms especially natural enemies (Croft, 1990; Shi *et al.*, 2005; Maniania *et al.*, 2008).

Biocontrol agents are generally discussed as safe alternatives for the management of pest mites (Wekesa *et al.*, 2015), as they are compared to selective chemical pesticides and can be the main component of integrated mite management programs (Ullah and Lim, 2017). Among different biocontrol agents, entomopathogenic fungi (EPF) have been considered as an inseparable part of integrated strategies for suppressing different mites and insect species (Wekesa *et al.*, 2006). *Beauveria bassiana* (Bals.) Vuill. play a critical role in management programs of numerous pest species (Irigaray *et al.*, 2003; Wekesa *et al.*, 2006; Maniania *et al.*, 2008; Seiedy *et al.*, 2010). Indeed, a possible effect on different mite species has been documented by several researchers (Maniania *et al.*, 2008; Geroh *et al.*, 2015). The usage of EPF in biological control is increasing mostly because of greater environmental awareness, food safety concerns, and the failure of conventional chemicals due to an increasing number of insecticide-resistant species (Shahid *et al.*, 2012; Yuan *et al.*, 2018). Keeping these advantages in view, several limitations (I: need specific environmental conditions; II: short shelf life; III:

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Table 1. Toxicity of *Beauveria bassiana* strain TV on female individuals of *Tetranychus urticae*

		Sub-lethal concentrations (conidia ml^{-1})*						
No.*	df	LC_{10} (confidence limits)	LC_{20} (confidence limits)	LC_{30} (confidence limits)	LC_{50} (confidence limits)	Slope ± SE	χ^2	*P*
640	5	6.76×10^2 (2.29×10^2–16.14×10^2)	8.74×10^3 (4.01×10^3–16.88×10^3)	55.38×10^3 (29.84×10^3–97.11×10^3)	11.70×10^5 (6.71×10^5–21.44×10^5)	2.69 ± 0.30	3.90	0.007

often slow acting and require high application rate (Maina *et al.*, 2018)) could drastically affect the biological performance of these natural enemies, and among them, reception of sub-lethal concentrations has considerable potential (He *et al.*, 2013; Song *et al.*, 2013).

Little or non-toxic to non-target organisms; the narrow area of toxic action; residues have no known adverse effects on the environment; reduce chemical insecticide use; self-perpetuating under ideal environmental conditions are some of the benefits of EPF (Maina *et al.*, 2018). Sub-lethal effects of fungal pathogens can have important conceptions on the population density of related hosts, which finally contributes to the status of the target organisms as a pest (Arthurs and Thomas, 2000; Blanford and Thomas, 2001; Hornbostel *et al.*, 2004; Quesada-Moraga *et al.*, 2004; Seyed-Talebi *et al.*, 2012).

Demographic toxicology has been suggested as the best way to evaluate total effects (lethal and sub-lethal) of entomopathogens, because it is based on both survivorship and fecundity parameters (Stark and Banks, 2003; Sedaratian *et al.*, 2013, 2014; Liu *et al.*, 2019). Considering the potential effects of sub-lethal exposure to EPF (*B. bassiana*) on pest populations, this study's objective is to improve the management of *T. urticae*.

Materials and methods

Host plant and mites

Host plant (*Cucumis sativus* L. cv. Veolla F_1 (Cucurbitaceae)) was grown in plastic pots (10 cm height, 5 cm diameter) under controlled greenhouse condition (25 ± 5°C, 60 ± 10% RH, and a photoperiod of 16: 8 (L: D) hours). To prevent unwanted infestations, all plants were maintained in mesh cages (1.5 × 1 × 1 m). The initial population of *T. urticae* was collected from infected greenhouses of Pakdasht (South-Eastern part of Tehran, Iran); which had been never exposed to pesticides. The spider mites were transferred to the greenhouse conditions and released on cucumber plants after being identified in the laboratory.

Fungus

In the current study, a native strain (TV) of *B. bassiana* (soil origin) was obtained from the College of Agriculture and Natural Resource, University of Tehran (Tehran, Iran). This strain was grown on Potato Dextrose Agar (PDA) and maintained at 25 ± 2°C, 70 ± 5% RH, and darkness photoperiod for 2 weeks to reach the sporulation stage. Cultures were scrapped after sporulation (≈14 days) and conidia were used for experimentations (Goettel and Inglis, 1997). To prepare a homogenous suspension of conidia, the conidia harvested from the surface of the Petri dishes vortexed with distilled water in a 100 ml tube for 20 min. The mixture is passed through Whatman No. 1 filter paper to separate the spores. The spore concentration was then determined using a hemocytometer slide under a microscope (ZIESS®) with 40× magnification (Sumikarsih *et al.*, 2019).

Bioassay

In bioassays, the following were used: seven fungal concentrations (10^2, 10^3, 10^4, 10^5, 10^6, 10^7, and 10^8 conidia ml^{-1}) that the mortality covering the range of 10–90%, and control treatment, where adult was treated with distilled water +0.02% Tween-80. Additionally, 20 same-aged adult mites (24 h-old ten males and ten females) were placed on the treated leaf discs (4 cm diameter) for each concentration by using a soft pointed brush. Then, the leaf discs of cucumber were sprayed (Posada *et al.*, 2007) with one of the different concentrations (10^2, 10^3, 10^4, 10^5, 10^6, 10^7, and 10^8 conidia ml^{-1} and control treatment) of *B. bassiana* and then, were dried for 30 min at room conditions. After this period of time, the Petri dishes lid was closed and the leaf discs were transferred to the incubator. The experiments were conducted at the laboratory conditions of 25 ± 2°C, 70 ± 5% RH and 16:8 (L:D) hours photoperiod.

Twenty-four hours later, the lids were replaced with new ones which had a hole in their center (4 cm diameter). These holes were covered with fine net mesh. After the leaf discs were inoculated with different concentrations of *B. bassiana*, initial mortality was counted after 5–7 days. Mites were considered dead when they did not move after stimulation. Each bioassay was replicated four times for each of the seven concentrations and control.

Life-table assay

To assess the sub-lethal effects of *B. bassiana* (LC_{10}, LC_{20}, and LC_{30}) on the biological parameters of *T. urticae*, 50 adult mites were transferred into fresh cucumber leaf discs (4 cm diameter), each of which was placed on a wet cotton in a Petri dish. The leaf discs were treated with distilled water and sub-lethal concentrations of *B. bassiana* (table 1). After 72 h, dead mites were removed and surviving females were separately transferred onto untreated discs (4 cm diameter) and allowed to oviposit for 24 h. After this period of time, one egg was selected randomly and transferred into a new leaf disc. In this way, 70 eggs were used for the experiments in each sublethal concentration. All experiments were conducted in a growth chamber at 25 ± 2°C, 70 ± 5% RH, and a photoperiod of 16:8 (L:D) h, while the development and survival time were checked daily. After adult emergence, female individuals were coupled with males from the same treatment. Adult longevity and their survivorship were documented every day. Daily fecundity of female mites was also recorded. Observations were performed until the death of the last individual.

Data analysis

To calculate the sub-lethal concentrations of *B. bassiana* and their 95% fiducial limits, Probit analysis was performed (SPSS ver. 19.0). The original raw data for all individuals were analyzed according to the age-stage, two-sex life table procedure (Chi and Liu, 1985; Chi, 1988), and computer program, TWOSEX

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Table 2. The effect of different concentrations of *Beauveria bassiana* on the duration of different life stages (mean ± SE) of *Tetranychus urticae*

Life stages and fecundity	Control	LC_{10}	LC_{20}	LC_{30}
Male				
Egg (day)	4.1 ± 0.1b	4.6 ± 0.11a	4.6 ± 0.12a	4.2 ± 0.1b
Larva (day)	2.0 ± 0.0a	2.0 ± 0.08a	1.8 ± 0.08a	1.8 ± 0.0a
Protonymph (day)	2.0 ± 0.1a	2.0 ± 0.08a	1.8 ± 0.09 a	1.7 ± 0.1a
Deutonymph (day)	1.8 ± 0.1a	1.7 ± 0.10a	1.6 ± 0.12a	1.5 ± 0.1a
Adult lifespan (day)	11.0 ± 0.2a	9.2 ± 0.21b	7.8 ± 0.29c	7.0 ± 0.2c
Total life span (day)	20.9 ± 0.3a	19.4 ± 0.43b	17.8 ± 0.38c	16.3 ± 0.3d
Female				
Egg (day)	4.4 ± 0.0a	4.2 ± 0.0ab	4.1 ± 0.0ab	4.0 ± 0.0b
Larva (day)	2.3 ± 0.0a	2.1 ± 0.0ab	2.0 ± 0.0b	1.8 ± 0.0b
Protonymph (day)	2.1 ± 0.0a	2.0 ± 0.0a	1.8 ± 0.0ab	1.7 ± 0.0b
Deutonymph (day)	2.0 ± 0.0a	1.9 ± 0.0ab	1.7 ± 0.0b	1.7 ± 0.0b
Adult lifespan (day)	12.3 ± 0.1a	11.8 ± 0.1a	10.4 ± 0.1b	9.6 ± 0.1c
Total life span (day)	23.3 ± 0.2a	22.0 ± 0.1b	20.2 ± 0.1c	19.0 ± 0.2d

Means within a row followed by the same letter are not significantly different (paired bootstrap test, $P < 0.05$).

MSChart (Chi, 2019). All population parameters including gross (GRR) and net (R_0) reproductive rates, intrinsic (r) and finite (λ) rates of increase as well as mean generation time (T) were estimated by bootstrap procedure using ×100,000 samples. Furthermore, the paired bootstrap test was used to evaluate statistical differences among different biological parameters of *T. urticae* (Efron and Tibshirani, 1993; Huang and Chi, 2012). The paired bootstrap test based on the confidence interval of differences was used to assess the differences between treatments (Wei *et al.*, 2020; Yang *et al.*, 2020).

Results

Concentration-response bioassay

The estimated LC_{50} for the *B. bassiana* was 11.70×10^5 conidia ml^{-1}; while no mortality was recorded at control treatment. In addition, the values of LC_{10}, LC_{20}, and LC_{30} were 6.77×10^2, 8.75×10^3, and 55.38×10^3 conidia ml^{-1}, respectively (table 1).

Sub-lethal effects on different developmental stages and fecundity

Table 2 presents the sub-lethal effects of *B. bassiana* on different developmental stages of both female and male individuals of *T. urticae*. Based on the results, a significant difference was observed between male (egg stage) and female individuals (in the duration of egg [$F = 7.15$, $P = 0.0003$, df = 3,68; female: $F = 4.76$, $P = 0.0033$, df = 3,168], larvae [male: $F = 1.35$, $P = 0.26$, df = 3,68; female: $F = 9.65$, $P < 0.0001$, df = 3,168] and protonymph [male: $F = 1.87$, $P = 0.14$, df = 3,68; female: $F = 7.34$, $P < 0.0001$, df = 3168] as well as deutonymph [male: $F = 1.99$, $P = 0.12$, df = 3,68; female: $F = 6.55$, $P < 0.0001$, df = 3,168] stages). The higher values for developmental stages at male and female individuals were observed in control and LC_{10} concentration. When the individuals were treated with LC_{30} of *B. bassiana*, males and adult lifespan of females, as well as total life span, were significantly affected. Adult lifespan and total life span of female individuals had the lowest values when LC_{30} treatment was applied (table 2).

Ovipositional period and total fecundity

The females treated by the LC_{20} and LC_{30} concentrations of *B. bassiana* had significant shorter total pre-oviposition periods (APOP: the duration from female emergence to first oviposition; TPOP: duration from egg to first oviposition) compared to the other treatments. The value of TPOP ranged from 10.3 to 11.9 days at LC_{30} and Control treatments, respectively.

The adult pre-ovipositional period (APOP) was not significantly affected by different concentrations of *B. bassiana* (table 3). The lowest duration of ovipositional period was 7.5 days at LC_{30}. *Beauveria bassiana* had significant sub-lethal effects on the total fecundity of *T. urticae* (table 3). Fecundity of female individuals was lowest at LC_{30} (18.2 eggs); whereas at Control treatment it was markedly higher (45.1 eggs).

Age-specific survivorship, age-specific and age-stage specific fecundity

The age-stage specific survival rates (s_{xj}) of *T. urticae* in different treatments are presented in fig. 1. Overlap between different developmental stages of *T. urticae* at different treatments was related to the variation of development rate of these biological stages (figs 1a–d). Age-specific survivorship (l_x), age-specific fecundity (m_x), and age-stage specific fecundity (f_{xj}) of *T. urticae* at different concentrations of *B. bassiana* are plotted in fig. 2. Total lifetime for *T. urticae* was 26, 25, 23, and 22 days in Control, LC_{10}, LC_{20}, and LC_{30} treatments, respectively. The highest value of m_x for control mites was 3.7 eggs/female which was observed on day 17. However, maximum values of m_x for LC_{10}, LC_{20}, and LC_{30} treatments were 3.1, 2.6, and 2.0 eggs/female which occurred on days 16, 15, and 13, respectively (fig. 2).

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Table 3. Mean (±SE) reproductive period and total fecundity of offspring from females of *Tetranychus urticae* for control and different concentrations of *Beauveria bassiana*

Parameters	Control	LC_{10}	LC_{20}	LC_{30}
APOP (day)[a]	1.0 ± 0.0a	1.0 ± 0.0a	1.0 ± 0.0a	1.0 ± 0.1a
TPOP (day)[b]	11.9 ± 0.2a	11.4 ± 0.1a	10.7 ± 0.1b	10.3 ± 0.1b
Ovipositional period (day)	10.3 ± 0.1a	9.8 ± 0.1b	8.3 ± 0.1b	7.5 ± 0.1c
Fecundity (egg)	45.1 ± 0.7a	36.2 ± 0.7b	23.9 ± 0.5c	18.2 ± 0.4d

Means within a row followed by the same letter are not significantly different (paired bootstrap test, $P < 0.05$).
[a]APOP = adult pre-ovipositional period (the duration from adult emergence to the first oviposition).
[b]TPOP = total pre-ovipositional period (the time between egg to the first oviposition).

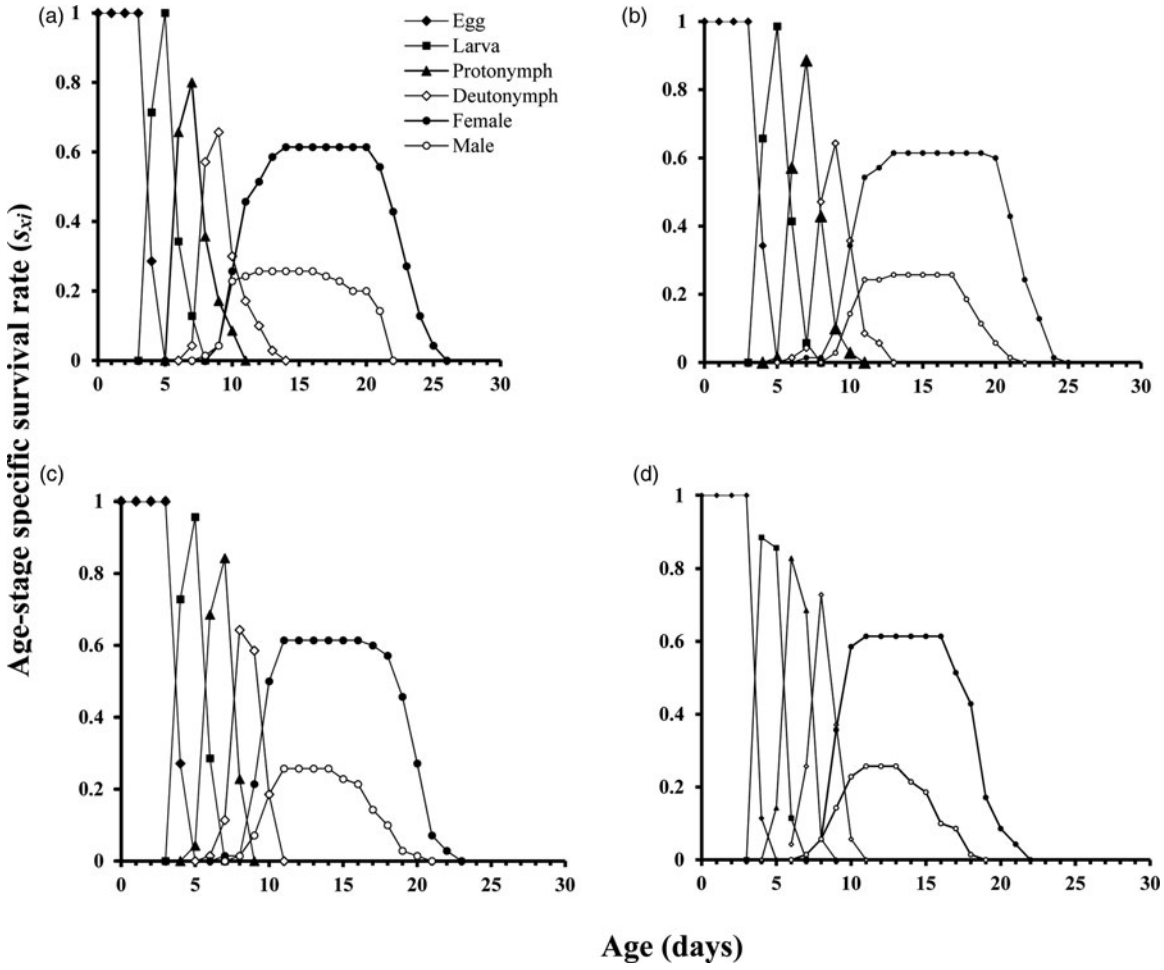

Fig. 1. The age-stage specific survival rate (s_{xj}) of *Tetranychus urticae* at different sub-lethal concentrations (a = Control, b = LC_{10}, c = LC_{20}, and d = LC_{30}) of *Beauveria bassiana*.

Population parameters

As displayed in table 4, different treatments drastically affected the population parameters of *T. urticae*. The gross reproductive rate (GRR) varied from 15.3 to 35.8 offspring/individual at LC_{30} and control treatments, respectively. Also, the lowest value of net reproductive rate (R_0) was obtained for the mites exposed to the LC_{30} treatment. The assessed intrinsic rate of increase (r) for mites influenced by sub-lethal concentrations ranged from 0.168 (day^{-1}) at LC_{30} to 0.198 (day^{-1}) in the control, respectively. The finite rate of increase (λ) indicated a significant difference with increasing concentration from control to LC_{30}. The mean generation time (T) had the highest value at control (16.7 days); followed by LC_{10}, LC_{20}, and LC_{30} (table 4).

Discussion

Although pesticides are considered as an economic, labor-saving, and efficient tool of pest management with great popularity in most sectors of the agricultural production, several undesirable effects have restricted their applications in modern agricultural systems (Kaplan *et al.*, 2012). Accordingly, there is a critical

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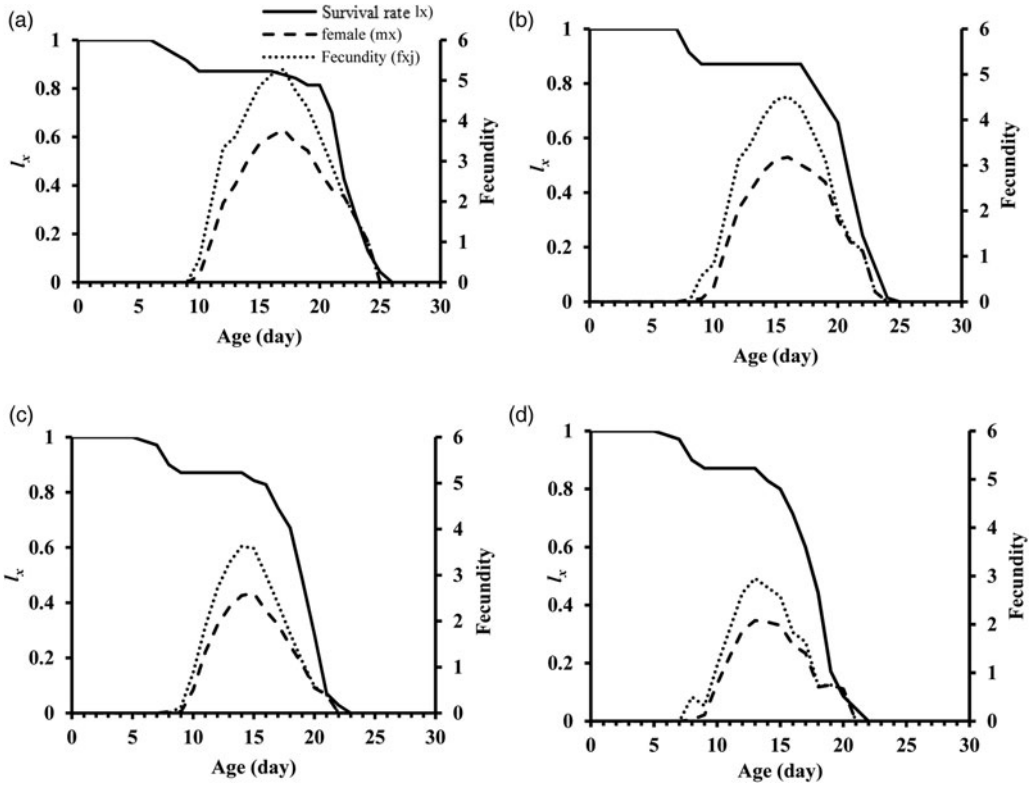

Fig. 2. Age-specific survivorship (l_x), age-specific fecundity (m_x), and age-stage specific fecundity (f_{xj}) of *Tetranychus urticae* at different sub-lethal treatments (a = Control, b = LC_{10}, c = LC_{20}, and d = LC_{30}) of *Beauveria bassiana.*

Table 4. The effects of different treatments of *Beauveria bassiana* on the population parameters (mean ± SE) of *Tetranychus urticae*

Treatments	Gross reproduction rate (GRR)	Net reproductive rate (R_0)	Intrinsic rate of increase (r)	Finite rate of increase (λ)	Mean generation time (T)
Control	35.8 ± 2.5a	27.7 ± 2.6a	0.198 ± 0.003a	1.219 ± 0.01a	16.7 ± 0.1a
LC_{10}	28.3 ± 1.9b	22.2 ± 2.1a	0.194 ± 0.005a	1.214 ± 0.04a	15.9 ± 0.1b
LC_{20}	18.9 ± 1.4c	14.7 ± 1.4b	0.179 ± 0.004b	1.196 ± 0.05b	14.9 ± 0.1c
LC_{30}	15.3 ± 1.1c	11.1 ± 1.0b	0.168 ± 0.007b	1.183 ± 0.02b	14.2 ± 0.1d
Unit	Offspring/individual	Offspring/individual	Day^{-1}	Day^{-1}	Day^{-1}

Means within a column followed by the same letter are not significantly different (paired bootstrap test, $P < 0.05$).

demand to find reliable alternatives for the sustainable management of phytophagous pests. Chandler *et al.* (2000) reviewed the opportunities of exploiting entomopathogens for biological control of phytophagous mites. However, consideration of EPF effects should be assessed further to specify its influence on offsprings' life history, including growth, development, and reproduction (Latifian *et al.*, 2010). Numerous studies have been conducted for evaluating the lethal and sub-lethal effects of different EPF such as *B. bassiana* and *Metarhizium anisopliae* Metchinkoff on *Tetranychus* species (Wekesa *et al.*, 2006; Shi and Feng, 2009; Seyed-Talebi *et al.*, 2014; Wu *et al.*, 2016). However, no evidence is available regarding the sub-lethal effects of *B. bassiana* on the biological attributes (such as survival, longevity, fecundity, and demographic parameters) of *T. urticae*.

Our findings revealed an obvious variation in susceptibility at different life stages of *T. urticae* to *B. bassiana*. In contrast with our results, Zhou *et al.* (2010) concluded that sub-lethal doses of *Isaria fumosorosea* Wize had no significant effects on developmental stages of *Axinoscymnus cardilobus* Ren and Pang (Coleoptera: Coccinellidae).

The adult longevity and total lifespan for both sexes were significantly lower in fungus-treated individuals than Control. Our results are in agreement with those reported by Irigaray *et al.* (2003) and Gatarayiha *et al.* (2010) which reported that *B. bassiana* had greater deleterious effects on adult females of *T. urticae* than immature stages. Afifi *et al.* (2010) reported that mite mortality was increased with increasing conidia concentration and exposure time to *B. bassiana*. Their results indicated that 14 days after treatment with 2×10^6 and 2×10^8 conidia ml^{-1}, an average mortality of 62.5 and 83.3% for *Panonychus ulmi* (Koch) and 82.6 and 91.7% for *Phyllocoptruta oleivora* Ashmed were recorded, respectively. On the other hand, *B. bassiana* strain 447 had no significant effects on *T. urticae* under laboratory conditions, even when applied at a concentration of

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1×10^9 conidia ml^{-1} (Antonio *et al.*, 1999). Several factors may be responsible for this variation in the efficacy of *B. bassiana* against spider mites, including strain identity, concentrations used, experimental conditions, host species and life stages, exposure time, etc.

Our study showed that sub-lethal concentrations of *B. bassiana* drastically reduced reproductive parameters of *T. urticae* in comparison with untreated individuals. The present study, however, exhibited that *B. bassiana* had no detectable effects on pre-ovipositional period of *T. urticae*. Our findings indicated negative effects of sub-lethal treatments on ovipositional period and total fecundity of *T. urticae*. These observations are in line with those reported by Shi and Feng (2009) in the case of *B. bassiana* strain Bb2860, *Paecilomyces fumosoroseus* and strain Pfr116 and *M. anisopliae* strain Ma759 on the *T. urticae*. Similarly, Ullah and Lim (2017) illustrated that *B. bassiana* strain GHA significantly decreased the fecundity of *T. urticae*. This evidence might be derived from a decrease in the female physiological state related to: (i) fungal colonization of tissues such as fat body (source of vitellogenins) and ovaries (Blay and Yuval, 1999) and (ii) fungal toxin production to transcend insect cellular and humeral immune reactions (Inglis *et al.*, 2001; Quesada-Moraga *et al.*, 2004). It has been shown that applying the sub-lethal concentrations of *B. bassiana* strain GZGY-1-3 had no significant effects on the fecundity of *Frankliniella occidentalis* (Pergande) (Zhang *et al.*, 2015).

The life table technique has been applied as a reliable procedure for assessing the population dynamics of both phytophagous organisms and their natural enemies (Biondi *et al.*, 2013; Cira *et al.*, 2017; Nawaz *et al.*, 2017). Regarding the curves of the age-specific survivorship (l_x) and age-specific fecundity (m_x) of *T. urticae* at different treatments, increasing sub-lethal concentrations had detectable effects on the mortality rate and fecundity of this pest. Similar reports were published for the survivorship schedules of *T. urticae*, *F. occidentalis*, *Encarsia formosa* Gahan, and *Planococcus citri* Risso when treated by *B. bassiana* strain 432.99, *B. bassiana* strian SZ-26, and *Lecanicillium longisporum* strain LRC190 and *L. longisporum*, respectively (Chandler *et al.*, 2000; Wu *et al.*, 2014; Fazeli-Dinan *et al.*, 2016; Ghaffari *et al.*, 2017). Among different population parameters, the intrinsic rate of increase (r) has been considered as the most applicable index that takes both fecundity and survivorship of individuals into account. The results obtained herein revealed that higher concentrations of *B. bassiana* obviously affected the r value of *T. urticae*. Likewise, Seyed-Talebi *et al.* (2012) and Rashki and Shirvani (2013) reported that the r and λ values were significantly lower in *T. urticae* and *Aphis gossypii* Glover which were treated with strains EUT105 and DEBI008 of *B. bassiana*, respectively. Despite our results, Baverstock *et al.* (2006) showed that *B. bassiana* has no significant effects on the r value of pea aphid, *Acyrthosiphon pisum* (Harris). It can also be hypothesized that feeding deficiency caused by fungal infection may drastically affect the reproductive potential of female individuals which have great energetic demands (Yuan *et al.*, 2018). In addition to these parameters, the values of net (R_0) and gross (GRR) reproduction rates and mean generation time (T) in treated individuals were also inferior to Control treatment. Similar to our findings, Huang *et al.* (2010) and Yuan *et al.* (2018) documented significant effects of different concentrations of *I. fumosoroseus* and *B. bassiana* strain JLGZL-14 on the R_0 and T values of *Bemisia tabaci* (Gennadius) and *Phthorimaea operculella* Zeller, respectively.

In conclusion, the present study displayed that *B. bassiana* not only has considerable pathogenicity to *T. urticae*, but also causes different sub-lethal effects such as reducing the total life-span as well as total fecundity of female individuals. Furthermore, our results clarified the considerable potential of *B. bassiana* strain TV, as an efficient biocontrol agent for sustainable management of *T. urticae*. More attention, however, should be devoted to investigate these effects under semi-field and field conditions.

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References

Abou El-Ela AA (2014) Efficacy of five acaricides against the two-spotted spider mite *Tetranychus urticae* Koch and their side effects on some natural enemies. *The Journal of Basic & Applied Zoology* **67**, 13–18.

Afifi AAM, Mabrouk AM and Asran AA (2010) Effect of the entomopathogenic fungus *Beauveria bassiana* on three acarine pests. In Sabelis M and Bruin J (eds), *Trends in Acarology*. Dordrecht: Springer, pp. 439–440.

Antonio TM, Batista AS and Janeiro NP (1999) Patogenicidade De *Beauveria bassiana* (Bals.) Vuill. AO ÁCARO *Tetranychus urticae* Koch. *Scientia Agricola* **56**, 285–288.

Arthurs S and Thomas MB (2000) Effects of a Mycoinsecticide on feeding and fecundity of the Brown locust *Locustana pardalina*. *Biocontrol Science and Technology* **10**, 321329.

Azadi-Qoort A, Sedaratian-Jahromi A, Haghani M and Ghane-Jahromi M (2019) Biological responses of *Tetranychus urticae* (Acari: Tetranychidae) to different host plants: an investigation on bottom-up effects. *Systematic & Applied Acarology* **24**, 659–674.

Baverstock J, Roy HE, Clark SJ, Alderson PG and Pell JK (2006) Effect of fungal infection on the reproductive potential of aphids and their progeny. *Journal of invertebrate pathology* **91**, 136–139.

Biondi A, Zappala L, Stark JD and Desneux N (2013) Do biopesticides affect the demographic traits of a parasitoid wasp and its biocontrol services through sublethal effects? *PLoS ONE* **8**, 1–11.

Blanford S and Thomas MB (2001) Adult survival, maturation, and reproduction of the desert locust *Schistocerca gregaria* infected with the fungus *Metarhizium anisopliae* var acridum. *Journal of Invertebrate Pathology* **78**, 1–8.

Blay S and Yuval B (1999) Oviposition and fertility in the Mediterranean fruit fly (Diptera: Tephritidae): effects of male and female body size and the availability of sperm. *Annals of Entomological Society of America* **89**, 486–492.

Campbell RJ, Mobley KN and Marini RP (1990) Growing conditions influence mite damage on apple and peach leaves. *HortScience* **25**, 445–448.

Chandler D, Davidson G, Pell JG, Ball BV, Shaw K and Sunderland KD (2000) Fungal biocontrol of Acari. *Biocontrol Science and Technology* **10**, 357–384.

Chen Q, Liang X, Wu C, Gao J, Chen Q and Zhang Z (2019) Density threshold-based acaricide application for the two-spotted spider mite *Tetranychus urticae* on cassava: from laboratory to the field. *Pest Management Science* **75**, 2634–2641.

Chi H (1988) Life-table analysis incorporating both sexes and variable development rates among individuals. *Environmental Entomology* **17**, 26–34.

Chi H (2019) *Twosex-Mschart: A Computer Program for the Agestage, Two-sex Life Table Analysis*. Taichung: National Chung Hsing University. http://140.120197.

Chi H and Liu H (1985) Two new methods for the study of insect population ecology. *Bulletin of the Institute of Zoology Academia Sinica* **24**, 225–240.

Cira TM, Burkness EC, Koch RL and Hutchison WD (2017) *Halyomorpha halys* mortality and sublethal feeding effects following insecticide exposure. *Journal of Pest Science* **90**, 1257–1268.

Croft BA (1990) *Arthropod Biological Control Agents and Pesticides*. New York: John Wiley.

Efron B and Tibshirani RJ (1993) Permutation tests. In *An Introduction to the Bootstrap*. New York, NY: Chapman & Hall, Inc., pp. 202–219.

https://doi.org/10.1017/S0007485321000523 Published online by Cambridge University Press

Fazeli-Dinan M, Talaei-Hassanloui R and Goettel M (2016) Virulence of the entomopathogenic fungus *Lecanicillium longisporum* against the greenhouse whitefly, *Trialeurodes vaporariorum* and its parasitoid *Encarsia formosa*. *International Journal of Pest Management* **62**, 251–260.

Gatarayiha MC, Laing MD and Miller RM (2010) Effects of adjuvant and conidial concentration on the efficacy of *Beauveria bassiana* for the control of the two spotted spider mite, *Tetranychus urticae*. *Experimental and Applied Acarology* **50**, 217–229.

Geroh M, Gulati R and Tehri K (2015) Determination of lethal concentration and lethal time of entomopathogen *Beauveria bassiana* (Balsamo) Vuillemin against *Tetranychus urticae* Koch. *International Journal of Agriculture Science* **7**, 523–528.

Ghaffari S, Karimi J, Kamali S and Moghadam EM (2017) Biocontrol of *Planococcus citri* (Hemiptera: Pseudococcidae) by *Lecanicillium longisporum* and *Lecanicillium lecanii* under laboratory and greenhouse conditions. *Journal of Asia-Pacific Entomology* **20**, 605–612.

Goettel MS and Inglis GD (1997) Fungi: hyphomycetes. In Lacey LA (ed.), *Manual of Techniques in Insect Pathology*. San Diego: Academic Press, pp. 213–251.

He Y, Zhao J, Zheng Y, Weng Q, Biondi A, Desneux N and Wu K (2013) Assessment of potential sublethal effects of various insecticides on key biological traits of the tobacco whitefly, *Bemisia tabaci*. *International Journal of Biological Sciences* **9**, 246–255.

Hornbostel VL, Ostfeld RS, Zhioua E and Benjamin MA (2004) Sublethal effects of *Metarhizium anisopliae* (Deuteromycetes) on engorged larval, nymphal, and adult *Ixodes scapularis* (Acari: Ixodidae). *Journal of Medical Entomology* **41**, 922–929.

Huang YB and Chi H (2012) Assessing the application of the jackknife and bootstrap techniques to the estimation of the variability of the net reproductive rate and gross reproductive rate: a case study in *Bactrocera cucurbitae* (Coquillett)(Diptera: Tephritidae). *Journal of Agriculture and Food Research* **61**, 37–45.

Huang Z, Ali S, Ren SX and Wu JH (2010) Effect of *Isaria fumosoroseus* on mortality and fecundity of *Bemisia tabaci* and *Plutella xylostella*. *Insect Science* **17**, 140–148.

Inglis GD, Goettel MS, Butt TM and Strasser H (2001) Use of hyphomycetous fungi for managing insect pests. In *Fungi as Biocontrol Agents: Progress Problems and Potential*, Wallingford, UK: CABI, pp. 23–69.

Irigaray FJSC, Marco-Mancebon V and Perez-Moreno I (2003) The entomopathogenic fungus *Beauveria bassiana* and its compatibility with triflumuron: effects on the two-spotted spider mite *Tetranychus urticae*. *Biological Control* **26**, 168–173.

Kaplan P, Yorulmaz S and Ay R (2012) Toxicity of insecticides and acaricides to the predatory mite *Neoseiulus californicus* (McGregor)(Acari: Phytoseiidae). *International Journal of Acarology* **38**, 699–705.

Khanamani M, Fathipour Y and Hajiqanbar H (2013) Population growth response of *Tetranychus urticae* to eggplant quality: application of female age-specific and age-stage, two-sex life tables. *International Journal of Acarology* **39**, 638–648.

Latifian M, Soleimannejadian E, Ghazavi M, Mosadegh MS and Hayati J (2010) Effects of sublethal concentrations of fungus *Beauveria bassiana* on the reproductive potentials of sawtoothed beetle *Oryzaephilus surinamensis* on commercial date cultivars. *Plant Protection Journal* **2**, 277–290.

Liu JF, Zhang ZQ, Beggs JR, Paderes E, Zou X and Wei XY (2019) Lethal and sublethal effects of entomopathogenic fungi on tomato/potato psyllid, *Bactericera cockerelli* (Šulc) (Hemiptera: Triozidae) in capsicum. *Crop Protection* **129**, 105023.

Maina UM, Galadima IB, Gambo FM and Zakaria D (2018) A review on the use of entomopathogenic fungi in the management of insect pests of field crops. *Journal of Entomology and Zoology Studies* **6**, 27–32.

Maleknia B, Fathipour Y and Soufbaf M (2016) How greenhouse cucumber cultivars affect population growth and two-sex life table parameters of *Tetranychus urticae* (Acari: Tetranychidae). *International Journal of Acarology* **42**, 70–78.

Maniania N, Bugeme D, Wekesa V, Delalibera I and Knapp M (2008) Role of entomopathogenic fungi in the control of *Tetranychus evansi* and *Tetranychus urticae* (Acari: Tetranychidae), pests of horticultural crops. *Experimental and Applied Acarology* **46**, 259–274.

Meck ED, Walgenbach JF and Kennedy GG (2012) Association of *Tetranychus urticae* (Acari: Tetranychidae) feeding and gold fleck damage on tomato fruit. *Crop Protection* **42**, 24–29.

Meck ED, Kennedy GG and Walgenbach JF (2013) Effect of *Tetranychus urticae* (Acari: Tetranychidae) on yield, quality, and economics of tomato production. *Crop Protection* **52**, 84–90.

Migeon A and Dorkeld F (2006–2017) Spider mites web: a comprehensive database for the Tetranychidae. Available at http://www.montpellier.inra.fr/CBGP/spmweb (Accessed 20 June 2017).

Mollaloo MG, Kheradmand K, Sadeghi R and Talebi AA (2017) Demographic analysis of sublethal effects of spiromesifen on *Neoseiulus californicus* (Acari: Phytoseiidae). *Acarologia* **57**, 571–580.

Nawaz M, Cai W, Jing Z, Zhou X, Mabubu JI and Hua H (2017) Toxicity and sublethal effects of chlorantraniliprole on the development and fecundity of a non-specific predator, the multicolored Asian lady beetle, *Harmonia axyridis* (Pallas). *Chemosphere* **178**, 496–503.

Park YL and Lee JH (2002) Leaf cell and tissue damage of cucumber caused by twospotted spider mite (Acari: Tetranychidae). *Journal of Economic Entomology* **95**, 952–957.

Posada F, Aime MC, Peterson SW, Rehner SA and Vega FE (2007) Inoculation of coffee plants with the fungal entomopathogen *Beauveria bassiana* (Ascomycota: Hypocreales). *Mycological research* **111**, 748–757.

Quesada-Moraga E, Santos-Quiros R, Valverde-Garcia P and Santiago-Alvarez C (2004) Virulence, horizontal transmission, and sublethal reproductive effects of *Metarhizium anisopliae* (Anamorphic fungi) on the German cockroach (Blattodea: Blattellidae). *Journal of Invertebrate Pathology* **87**, 51–58.

Rashki M and Shirvani A (2013) The effect of entomopathogenic fungus, *Beauveria bassiana* on life table parameters and behavioural response of *Aphis gossypii*. *Bulletin of Insectology* **66**, 85–91.

Sedaratian A, Fathipour Y and Moharramipour S (2009) Evaluation of resistance in 14 soybean genotypes to *Tetranychus urticae* (Acari: Tetranychidae). *Journal of Pest Science* **82**, 163–170.

Sedaratian A, Fathipour Y and Moharramipour S (2011) Comparative life table analysis of *Tetranychus urticae* (Acari: Tetranychidae) on 14 soybean genotypes. *Insect Science* **18**, 541–553.

Sedaratian A, Fathipour Y, Talaei-Hassanloui R and Jurat-Fuentes JL (2013) Fitness costs of sublethal exposure to *Bacillus thuringiensis* in *Helicoverpa armigera*: a carryover study on offspring. *Journal of Applied Entomology* **137**, 540–549.

Sedaratian A, Fathipour Y and Talaei-Hassanloui R (2014) Deleterious effects of *Bacillus thuringiensis* on biological parameters of *Habrobracon hebetor* parasitizing *Helicoverpa armigera*. *BioControl* **59**, 89–98.

Seiedy M, Saboori A, Allahyari H, Talaei-Hassanloui R and Tork M (2010) Laboratory investigation on the virulence of two isolates of the entomopathogenic fungus *Beauveria bassiana* against the two spotted spider mite, *Tetranychus urticae* (Acari: Tetranychidae). *International Journal of Acarology* **36**, 527–532.

Seyed-Talebi FS, Kheradmand K, Talaei-Hassanloui R and TalebiJahromi K (2012) Sublethal effects of *Beauveria bassiana* on life table parameters of two-spotted spider mite, *Tetranychus urticae* (Acari:Tetranychidae). *Biocontrol Science and Technology* **22**, 293–303.

Seyed-Talebi FS, Kheradmand K, Talaei-Hassanloui R and Talebi-Jahromi K (2014) Synergistic effect of *Beauveria bassiana* and spirodiclofen on the two-spotted spider mite (*Tetranychus urticae*). *Phytoparasitica* **42**, 405–412.

Shahid AA, Rao QA, Bakhsh A and Husnain T (2012) Entomopathogenic fungi as biological controllers: new insights into their virulence and pathogenicity. *Archives of Biological Sciences* **64**, 21–42.

Shi WB and Feng MG (2009) Effect of fungal infection on reproductive potential and survival time of *Tetranychus urticae* (Acari: Tetranychidae). *Experimental and Applied Acarology* **48**, 229–237.

Shi WB, Jiang Y and Feng MG (2005) Compatibility of ten acaricides with *Beauveria bassiana* and enhancement of fungal infection to *Tetranychus cinnabarinus* (Acari: Tetranychidae) eggs by sublethal application rates of pyridaben. *Applied Entomology and Zoology* **40**, 659–666.

https://doi.org/10.1017/S0007485321000523 Published online by Cambridge University Press

Song Z, Zhang B, Li D and Zheng Y (2013) Effects of abamectin on the survival and development of *Neoseiulus fallacis* (Garman). *Chinese Journal of Biological Control* **29**, 349–353.

Stark JD and Banks JE (2003) Population level effects of pesticides and other toxicants on arthropods. *Annual Review of Entomology* **48**, 505–519.

Sumikarsih E, Herlinda S and Pujiastuti Y (2019) Conidial density and viability of *Beauveria bassiana* isolates from Java and Sumatra and their virulence against *Nilaparvata lugens* at different temperatures. AGRIVITA. *Journal of Agricultural Science* **41**, 335–350.

Tomczyk A and Kropczynska D (1985) Effects on the host plant. In Helle W and Sabelis MW (eds), *Spider Mites: Their Biology, Natural Enemies and Control*. New York, NY: Elsevier Science Publisher, pp. 317–327.

Ullah MS and Lim UT (2017) Synergism of *Beauveria bassiana* and *Phytoseiulus persimilis* in control of *Tetranychus urticae* on bean plants. *Systematic and Applied Acarology* **22**, 1924–1936.

van Leeuwen T, Vontas J, Tsagkarakou A, Dermauw W and Tirry L (2010) Acaricide resistance mechanisms in the two-spotted spider mite *Tetranychus urticae* and other important acari: a review. *Insect Biochemistry and Molecular Biology* **40**, 563–572.

Wei M, Chi H, Guo Y, Li X, Zhao L and Ma R (2020) Demography of *Cacopsylla chinensis* (Hemiptera: Psyllidae) reared on four cultivars of *Pyrus bretschneideri* (Rosales: Rosaceae) and *P. communis* pears with estimations of confidence intervals of specific life table statistics. *Journal of Economic Entomology* **113**, 2343–2353.

Wekesa VW, Knapp M, Maniania NK and Boga HI (2006) Effects of *Beauveria bassiana* and *Metarhizium anisopliae* on mortality, fecundity and egg fertility of *Tetranychus evansi*. *Journal of Applied Entomology* **130**, 155–159.

Wekesa VW, Hountondji FCC and Dara SK (2015) Mite pathogens and their use in biological control. In Carrillo D, José de Moraes G and Peña JE (eds), *Prospects for Biological Control of Plant Feeding Mites and Other Harmful Organisms*, vol. **19**. Cham: Springer International Publishing, pp. 309–328.

Wu S, Gao Y, Zhang Y, Wang E, Xu X and Lei Z (2014) An entomopathogenic strain of *Beauveria bassiana* against *Frankliniella occidentalis* with no detrimental effect on the predatory mite *Neoseiulus barkeri*: evidence from laboratory bioassay and scanning electron microscopic observation. *PLoS ONE* **9**, e84732.

Wu S, Xie H, Li M, Xu X and Lei Z (2016) Highly virulent *Beauveria bassiana* strains against the two-spotted spider mite, *Tetranychus urticae*, show no pathogenicity against five phytoseiid mite species. *Experimental and Applied Acarology* **70**, 421–435.

Yang X, Sun L, Chi H, Kang G and Zheng C (2020) Demography of *Thrips palmi* (Thysanoptera: Thripidae) reared on *Brassica oleracea* (Brassicales: Brassicaceae) and *Phaseolus vulgaris* (Fabales: Fabaceae) with discussion on the application of the bootstrap technique in life table research. *Journal of Economic Entomology* **113**, 2390–2398.

Yuan HG, Wu SY, Lei ZR, Rondon SI and Gao YL (2018) Sub-lethal effects of *Beauveria bassiana* (Balsamo) on field populations of the potato tuberworm *Phthorimaea operculella* Zeller in China. *Journal of Integrative Agriculture* **17**, 911–918.

Zhang T, Reitz SR, Wang H and Lei Z (2015) Sublethal effects of *Beauveria bassiana* (Ascomycota: Hypocreales) on life table parameters of *Frankliniella occidentalis* (Thysanoptera: Thripidae). *Journal of Economic Entomology* **108**, 975–985.

Zhou F, Ali S and Huang Z (2010) Influence of the entomopathogenic fungus *Isaria fumosorosea* on *Axinoscymnus cardilobus* (Coleoptera: Coccinellidae) under laboratory conditions. *Biocontrol Science and Technology* **20**, 709–722.