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Effect of temperature on the development of *Eotetranychus hirsti* (Tetranychidae) on fig leaves

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ABSTRACT — The fig spider mite, *Eotetranychus hirsti* is one of the major pests of fig trees worldwide. The effect of temperature on the developmental time and the survival rate of *E. hirsti* feeding on fig leaves was determined at six constant temperatures of 15, 20, 25, 30, 32 and 35 °C. The total developmental time of females (from egg to adult emergence) at the above-mentioned temperatures was 41.29, 24.15, 16.95, 12.35, 10.21 and 10.67 days, respectively. The lower, optimal and upper developmental threshold (T_{min} , T_{opt} and T_{max} , respectively) and thermal constant (K) of the pest were estimated by ordinary linear and Logan 6 nonlinear models. The lower temperature threshold (T_{min}) and thermal constant (K) of the immature stages were estimated to be 9.86 °C and 239.48 degree-days (DD), respectively. The T_{opt} and T_{max} were estimated to be 34.30 and 35.44 °C, respectively. As the temperature increased from 15 to 30 °C, the survival rate of immature stages increased from 33.33 to 70.59 %, then decreased and reached 54.91 % at 35 °C. Temperature-dependent development data, thermal requirements and temperature thresholds can be used to predict the occurrence, number of generations and population dynamics of *E. hirsti*.

KEYWORDS — immature stages; fig spider mite; temperature thresholds; mortality, thermal constant

INTRODUCTION

The fig spider mite, *Eotetranychus hirsti* Baker & Pritchard (Acari: Tetranychidae) is an important pest of fig trees in Iran and other world fig growing areas (Baradaran *et al.*, 2002). This phytophagous mite was reported for the first time by Hirst (1926) from India as *Tetranychus fici*. In 1940 Rahman and Sapra reported it from Pakistan under the same name. Later Pritchard and Baker (1955) transferred this species into the genus *Eotetranychus*. This mite had been reported from different regions of Iran mainly on fig trees (Beyzavi *et al.*, 2013). In Iran, the common fig (*Ficus carica* L.) is attacked simul-

taneously by *E. hirsti* and *Rhyncaphytoptus ficifoliae* Keifer (Diptilomiopidae) where it has negative effects on the fruit yield of this tree especially in summer. *Eotetranychus hirsti* is the key pest of fig trees in Iran and is mainly controlled by chemical pesticides (Khanjani and Hadad-Irani Nejad, 2006).

Temperature is the main abiotic factor that has profound effects on the life history of mites (Aponte and McMurtry, 1997; Liu and Tsai, 1998; Gotoh and Nagata, 2001; Jafari *et al.*, 2012; Ullah *et al.*, 2012; Lin, 2013; Bazgir *et al.*, 2015) and many experiments have proven that temperature plays a crucial role in developmental rates of arthropods (Shi and Ge,

2010). Temperature sets the limits of biological performance in arthropods; the critical temperatures (T_{min} , T_{opt} and T_{max}) can be considered for all major life processes, where within a specific range, a temperature change results in a proportional rise or fall of the rate of any given process (Roy *et al.*, 2002). Developmental rate, which is zero at the T_{min} , increases with increasing temperature and reaches its peak at the optimum temperature and then decreases rapidly as the higher threshold is approached (Roy *et al.*, 2002). The relationship between temperature and developmental rate is approximately linear at moderate temperatures and curvilinear near the extremes (Wagner *et al.*, 1984). Knowing the temperature requirements of the various life stages of a target species is an important instrument in forecasting its potential distribution and population dynamics. The ability of a pest to develop at different temperatures determines to a large extent its survival under different climatic conditions, which is important in predicting pest outbreaks (Ullah *et al.*, 2012).

Previous to this study, the biology of *E. hirsti* was studied at 30 °C by Daneshnia *et al.* (2013), but there is no available data regarding the effect of different temperatures on immature development and survival rate of this mite. Therefore, the aim of this study was to investigate the effect of broad range of temperatures on development and survival rate of *E. hirsti* immature stages in a laboratory study.

MATERIALS AND METHODS

All experiments were carried out in the Entomology laboratory at the Department of Plant Protection of Lorestan University, Khorramabad, Iran.

Rearing the colony of *Eotetranychus hirsti*

Fig leaves infested by *E. hirsti* were collected from fig orchards in Veisian region, Lorestan province, Western Iran, during summer 2014 and transferred to the laboratory. Colonies of *E. hirsti*, were reared on fig leaves at 27 ± 1 °C, 50 ± 5 % RH and a photoperiod of 16:8 (L:D) h. *E. hirsti* were maintained under laboratory conditions after two generations and then used for experiments.

Laboratory experiments

The duration of immature stages of *E. hirsti* was measured at six constant temperatures: 15, 20, 25, 30, 32 and 35 °C, with a relative humidity of 50 ± 5 % and a photoperiod of 16:8 (L:D) h. All experiments were performed using arenas consisting of a piece of fig leaf (4 cm in diameter), placed upside down on a water saturated foam mat covered with moist filter paper, inside plastic Petri dishes (6 cm in diameter) with a hole in their center (0.5 cm in diameter). Leaf discs were made with fresh fig leaves. Before the release of the mites, all unwanted organisms were removed from leaves by thoroughly brushing them and by examining under binocular microscope. To keep the freshness of leaves and prevent the escape of mites, the margins of fig leaves were covered with strips of moist cotton. The lids of Petri dishes had a big hole that was covered with fine mesh for ventilation. Each experimental arena was placed in a larger Petri dish (9 cm in diameter) filled with water. Plastic Petri dishes were kept in four incubators (Jal Tajhiz Company, Iran), which were able to control the RH, temperature and photoperiod. For measuring the immature development time of *E. hirsti* the 150 gravid females were transferred to 60 experimental arenas. After 12 h, the females and extra eggs were removed, and only one egg was kept on the detached fig leaf in each arena. Sixty eggs were used as a cohort at each temperature. Developmental time of all immature stages from egg to adult was checked daily. The presence of an exuvium was the criterion for successful moulting to the next stage. The mites were transferred to new arenas every three or four days. To determine the duration of the immature stages and survival rate of *E. hirsti*, inspections have been carried out every 12 h under a binocular microscope until the mites reached to adult stage.

Model evaluation

The reciprocal of developmental time in days is denoted as developmental rate. These rates are used in linear and non-linear models. An ordinary linear model was used to predict the developmental rate and estimate the lower temperature threshold (T_{min}) and thermal constant (K) of *E. hirsti*. The T_{min}

calculated as $-a/b$, where a and b are determined by the following linear regression model:

$$R = a + bT$$

where R is the development rate (days), T is the temperature ($^{\circ}\text{C}$), a and b are the regression coefficients. K is calculated as $1/b$ (Campbell *et al.*, 1974; Huffaker *et al.*, 1999).

The result of 35°C was excluded in the linear model due to being out with the linear portion of developmental rate. This omission for the correct estimation of the T_{min} is necessary (De Clerq and Degheele, 1992; Ikemoto and Takai, 2000; Jafari *et al.*, 2012).

A Logan 6 nonlinear model was used to describe the relationship between temperature and developmental rate and to estimate the upper temperature threshold (T_{max}) and optimum temperature threshold (T_{opt}) for immature stages of *E. hirsti* (Logan *et al.*, 1976). The following model, derived by Logan *et al.* (1976), was used to describe the relationship between the developmental rate of immature stages of *E. hirsti* and temperature:

$$D(T) = \Psi \times \left[e^{\rho \cdot T} - e^{\left(\rho \cdot T_{max} \frac{T_{max} - T}{\Delta T} \right)} \right]$$

where T is the rearing temperature ($^{\circ}\text{C}$), Ψ is the maximum developmental rate, ρ is a constant defining the rate at optimal temperature, T_{max} is the lethal maximum temperature, and ΔT is the temperature range over which physiological breakdown becomes the overriding influence thresholds (Logan *et al.*, 1976; Huffaker *et al.*, 1999). This model was chosen because it accurately described the developmental rates for other tetranychid mites (Logan *et al.*, 1976; Bonato *et al.*, 1990; Bounfour and Tanigoshi, 2001).

Data analyses

A Students t-test was used to determine the significant difference between the duration of immature stages of males and females ($P < 0.05$). The influence of temperatures on immature developmental time of *E. hirsti* was analysed using a one way

analysis of variance (ANOVA). When a significant difference was detected, the means of developmental time were compared using a Duncan multiple ranges test ($P < 0.05$). The ANOVA and mean comparisons were carried out using the SAS software (Pros GLM, SAS Institute, 2003). The temperature dependent models were analysed using SigmaPlot Software 2001 (SAS Institute, 2007).

RESULTS

Immature developmental time

The results show that *Eotetranychus hirsti* developed successfully to adulthood over a temperature range of $15 - 35^{\circ}\text{C}$ feeding on fig leaves. Table 1 shows the developmental time of immature stages of *E. hirsti* females and males at six temperatures. As shown in table 1, the effect of temperature on developmental time of females was significant for egg ($F = 323.03$; $df = 5,126$; $P < 0.0001$), larva ($F = 130.28$; $df = 5,126$; $P < 0.0001$), protochrysalis ($F = 122.29$; $df = 5,126$; $P < 0.0001$), protonymph ($F = 48.99$; $df = 5,126$; $P < 0.0001$), deutochrysalis ($F = 100.62$; $df = 5,126$; $P < 0.0001$), deutonymph ($F = 107.58$; $df = 5,126$; $P < 0.0001$), teliochrysalis ($F = 156.84$; $df = 5,126$; $P < 0.0001$) and whole immature stages ($F = 905.24$; $df = 5,126$; $P < 0.0001$). The duration of immature stages of females decreased as the temperature increased from 15 to 32°C , but slightly increased at 35°C . The incubation period was the longest stage ranging from 13.59 days at 15°C to 3.95 days at 32°C (Table 1). Temperature had a significant effect on incubation ($F = 126.67$; $df = 5,59$; $P < 0.0001$), larva ($F = 37.03$; $df = 5,59$; $P < 0.001$), protochrysalis ($F = 44.85$; $df = 5,59$; $P < 0.001$), protonymph ($F = 24.37$; $df = 5,59$; $P < 0.001$), deutochrysalis ($F = 53.16$; $df = 5,59$; $P < 0.001$), deutonymph ($F = 36.24$; $df = 5,59$; $P < 0.0003$), teliochrysalis ($F = 89.22$; $df = 5,59$; $P < 0.0001$) and total immature ($F = 276.49$; $df = 5,59$; $P < 0.001$) periods of males. Similar to females, total developmental time in males decreased as temperature increased from 15 to 32°C , but slightly increased at 35°C (Table 1). At 15°C ($T = 0.860$; $P = 0.415$), 20°C ($T = 1.385$; $P = 0.225$), 25°C ($T = 1.549$; $P = 0.142$), 30°C ($T = 1.771$; $P = 0.10$), 32°C ($T = 1.867$; $P = 0.104$) and 35°C ($T = 1.722$; $P =$

TABLE 1: Mean (\pm SE) developmental times (days) of *Eotetranychus hirsti* at six constant temperatures fed on fig leaves.

Stages	Temperature (°C)					
	15	20	25	30	32	35
Female						
Egg	13.59 \pm 0.38a	10.53 \pm 0.27b	7.86 \pm 0.18c	5.08 \pm 0.15d	3.95 \pm 0.14e	3.96 \pm 0.21e
Larva	4.88 \pm 0.19a	2.35 \pm 0.15b	1.71 \pm 0.16c	1.27 \pm 0.12c	0.93 \pm 0.09d	1.04 \pm 0.08d
Protochrysalis	4.29 \pm 0.22a	2.15 \pm 0.12b	1.09 \pm 0.07c	1.04 \pm 0.10c	1.08 \pm 0.12c	0.96 \pm 0.08c
Protonymph	3.94 \pm 0.26a	2.03 \pm 0.15b	1.67 \pm 0.25c	1.06 \pm 0.09d	0.98 \pm 0.07d	1.00 \pm 0.14d
Deutochrysalis	4.62 \pm 0.26a	2.29 \pm 0.13b	1.26 \pm 0.12c	1.42 \pm 0.09 bc	1.15 \pm 0.11c	1.36 \pm 0.09 c
Deutonymph	4.94 \pm 0.17a	2.47 \pm 0.16b	1.90 \pm 0.15c	1.27 \pm 0.11d	1.10 \pm 0.10d	1.25 \pm 0.11d
Teliochrysalis	5.03 \pm 0.24a	2.32 \pm 0.12b	1.45 \pm 0.11bc	1.21 \pm 0.11c	1.08 \pm 0.13c	1.07 \pm 0.11c
Immature stages	41.29 \pm 0.61a	24.15 \pm 0.50b	16.95 \pm 0.46c	12.35 \pm 0.34d	10.21 \pm 0.26d	10.67 \pm 0.27d
Male						
Egg	14.06 \pm 0.58a	9.67 \pm 0.33b	7.50 \pm 0.30c	4.93 \pm 0.22d	3.75 \pm 0.27d	3.14 \pm 0.14d
Larva	4.06 \pm 0.18a	1.33 \pm 0.21b	1.50 \pm 0.18b	1.36 \pm 0.13b	0.88 \pm 0.18c	1.07 \pm 0.18c
Protochrysalis	4.33 \pm 0.29a	1.50 \pm 0.23b	1.44 \pm 0.16b	1.11 \pm 0.15c	0.75 \pm 0.14d	0.93 \pm 0.07d
Protonymph	3.67 \pm 0.24a	1.83 \pm 0.31b	1.38 \pm 0.16c	1.80 \pm 0.19b	0.81 \pm 0.13d	1.21 \pm 0.15c
Deutochrysalis	3.94 \pm 0.24a	2.08 \pm 0.27 b	1.28 \pm 0.13 c	0.89 \pm 0.11 d	0.94 \pm 0.11 d	0.93 \pm 0.07d
Deutonymph	4.33 \pm 0.33a	2.33 \pm 0.36 b	1.56 \pm 0.16 c	1.14 \pm 0.14d	0.81 \pm 0.09 d	1.00 \pm 0.19d
Teliochrysalis	5.39 \pm 0.23a	1.92 \pm 0.33 b	1.38 \pm 0.13 b	0.93 \pm 0.10c	1.19 \pm 0.21bc	1.07 \pm 0.17c
Immature stages	39.78 \pm 1.23a	20.67 \pm 0.80b	16.03 \pm 0.53c	11.54 \pm 0.44 d	09.13 \pm 0.41 e	09.36 \pm 0.30e

Means followed by different letters within the same raw for each sex are significantly different ($P < 0.05$, Duncan's test).

0.136), there was no significant difference between the developmental time of males and females.

$^{\circ}\text{C} \pm 101.74$; $T_{opt} = 34.30$ $^{\circ}\text{C}$; $R^2_{adj} = 0.9881$; $AIC = -67.376$.

Ordinary linear model

The lower temperature threshold (T_{min}) and thermal constant (K) estimated by the ordinary linear model for each developmental stage of *E. hirsti* females are presented in table 2. The T_{min} values ranged from 7.58 to 11.16 $^{\circ}\text{C}$. The estimated T_{min} for overall immature stages was 9.86 $^{\circ}\text{C}$. The thermal constant (K) for whole immature stages of *E. hirsti* was 239.48 DD. The curve of the ordinary linear model, which was fitted to the developmental rate of overall immature stages of *E. hirsti*, is depicted in figure 1. According to R^2 values, the linear model showed an acceptable fit to the developmental rate of various immature stages of *E. hirsti* (Table 2).

The Logan 6 model was fitted appropriately to our data. The curve of the Logan 6 model, which was fitted to the developmental rate of overall immature stages of *E. hirsti* is shown in figure 1. The parameters estimated by the Logan 6 model were: $\Psi = 0.0087 \pm 0.0015$; $\Delta T = 0.294 \pm 65.18$; $T_{max} = 35.44$

Survival rate of immature stages

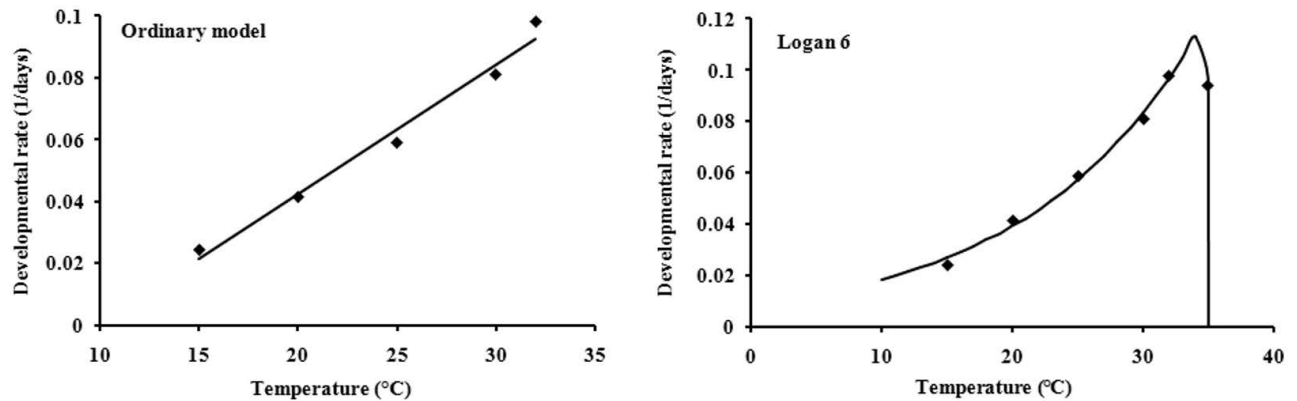
Table 3 shows the survival rate of immature stages of *E. hirsti* at the temperatures tested. The survival rate of immature stages ranged from 33.3 % at 15 $^{\circ}\text{C}$ to 70.59 % at 30 $^{\circ}\text{C}$. The lowest survival rate was for egg stages at all temperatures tested. The lowest and highest survival rate of eggs was recorded at 15 $^{\circ}\text{C}$ (66.67 %) and 30 $^{\circ}\text{C}$ (85.29 %), respectively.

DISCUSSION

These are the first data showing the influence of temperatures on the developmental times of the phytophagous mite *Eotetranychus hirsti*. This study shows that the developmental rate of the *E. hirsti* increases with temperature within a certain suitable range (15 – 32 $^{\circ}\text{C}$) with 35 $^{\circ}\text{C}$ causing a decrease in its developmental rate. In agreement with this finding, it is well known that the relationship between temperature and developmental rate in in-

TABLE 2: The estimated lower temperature threshold (T_{\min}), thermal constant (K) and the regression equation for various immature stages of *Eotetranychus hirsti* females fed on fig leaves by ordinary linear model.

Stage	T_{\min} (°C)	K (DD)	Regression equation	P -value	R^2
Egg	09.63	104.83	$Y = -0.0974 + 0.0101T$	0.012	90.7
Larva	11.16	21.49	$Y = -0.519 + 0.04654T$	0.006	94.5
Protochrysalis	08.62	22.52	$Y = -0.3830 + 0.04440T$	0.017	88.5
Protonymph	09.67	22.23	$Y = -0.435 + 0.04499T$	0.002	97.5
Deutochrysalis	07.58	27.84	$Y = -0.2720 + 0.0359T$	0.022	86.3
Deutonymph	10.37	24.81	$Y = -0.4177 + 0.0400T$	0.001	98.1
Teliochrysalis	09.88	23.60	$Y = -0.4186 + 0.0424T$	0.000	99.1
Immature stages	09.86	239.48	$Y = -0.0412 + 0.00418T$	0.001	98.1

FIGURE 1: Fitting ordinary linear and Logan 6 nonlinear models (lines) to observed values of the development rate for overall immature stages of *Eotetranychus hirsti* (dots) reared on fig leaves at six temperatures tested.TABLE 3: The survival rate of *Eotetranychus hirsti* immature stages at six constant temperatures fed on fig leaves.

Stage	Temperature (°C)					
	15	20	25	30	32	35
Egg	66.67	67.39	79.41	85.29	82.35	80.39
Larva	79.41	90.32	88.89	89.66	89.29	82.93
Protochrysalis	96.3	100	95.83	100	100	97.06
Protonymph	76.92	78.57	95.65	96.15	92	93.93
Deutochrysalis	90	95.46	100	100	95.66	96.77
Deutonymph	94.45	80.95	95.46	96	95.46	96.67
Teliochrysalis	100	100	100	100	95.24	96.55
Immature stages	33.33	36.96	61.77	70.59	58.82	54.91

sects is linear over most of the normal operating, middle range of temperature, but becomes sigmoid over the whole temperature range that permits development (Andrewartha and Birch, 1954; Jafari *et al.*, 2012; Zahiri *et al.*, 2012). Similar trends for some tetranychoid mites were reported (Liu and Tsai, 1998; Roy *et al.*, 2003; Ullah *et al.*, 2012; Lin, 2013; Riahi *et al.*, 2013).

In this research the temperature dependent development of the Iranian population of *E. hirsti* under the broad range of temperatures generally prevailing in this region was studied and its temperature thresholds determined. This study also revealed that the immature developmental period of *E. hirsti* is strongly affected by temperature. The developmental periods of *E. hirsti* are longer than those reported for some species of *Eotetranychus*. The immature developmental time of *Eotetranychus hicoriae* (McGregor) at 21.1, 26.7 and 32.2 °C was 24.3, 11.1 and 8.5 days, respectively (Jackson *et al.*, 1983). The duration of immature stages of *Eotetranychus carpini borealis* (Ewing) was 27.90, 18.4, 14.90 and 12 days at 15, 20, 25 and 30 °C, respectively (Bounfour and Tanigoshi, 2001), which are shorter than those observed in our study. Grissa-Lebdi *et al.* (2002) found an average developmental period of 13.7 and 14.5 days for two strains of *Eotetranychus pruni* (Oudemans), measured at 24 °C, that are shorter than our finding at 25 °C (16.95 days). The duration of immature stages of *Eotetranychus willamettei* McGregor was 34.05, 15.43, 12.55 and 10.8 days, at 15, 22, 25 and 28 °C, respectively (Stavrínides *et al.*, 2010). However, the developmental time of *E. hirsti* at 30 ± 1°C, 60 ± 10 % RH and 12: 12 h (dark: light) photoperiod was 11.56 days (Daneshnia *et al.*, 2013) which is close to our result at the same temperature (12.35 days). This small difference could be explained by a difference in experimental conditions (RH and photoperiod).

Although in the present study the duration of whole immature stages of females was longer than of males, there was no statistically significant difference between the developmental times of females and males. A similar result was reported for *Oligonychus mangiferus* (Rhaman and Sapra) by Lin (2013).

The importance of critical temperatures and thermal budgets for understanding the phenology of an arthropod has long been recognized (Luytjaert, 2014). Lower developmental thresholds and thermal constants are not only good predictors of the timing of life events, but are also very useful indicators for the potential distribution of the pest (Campbell *et al.*, 1974). Our study showed that a total of 239.48 degree-days above the threshold temperature was required for *E. hirsti* to complete development from egg to adult, which was higher than 113.3 DD for *Eotetranychus populi* (Koch) (Su Xugen *et al.*, 1996), 136.43 DD for *T. urticae* (Riahi *et al.*, 2013) and 200 DD for *Oligonychus perseae* Tuttle, Baker and Abbatiello (Aponte and McMurtry, 1997). In contrast, the reported value of *K* for *E. carpini borealis* (379.8 DD) (Bounfour and Tanigoshi, 2001) is greater than our finding.

The T_{min} for *E. hirsti* is estimated to be 9.86 °C, which is lower than 10.50 °C for *E. Willamettei* (Stavrínides *et al.*, 2010) and 13.79 °C for *T. urticae* (Riahi *et al.*, 2013). Conversely, Bonato *et al.* (1990) obtained 7 °C for *Eotetranychus carpini* (Oudemans) and Bounfour and Tanigoshi (2001) reported 2.29 °C as the T_{min} for *E. carpini borealis*, which is lower than our finding. The reported T_{min} for the overall immature stages of *E. populi* was 9.64 (Su Xugen *et al.*, 1996) that is relatively close to our result.

The reported T_{opt} for *Tetranychus macfarlanei* Baker & Pritchard (24.4 °C) (Ullah *et al.*, 2012) and *Bryobia rubrioculus* Scheuten (29.3 °C) (Javadi Khederi and Khanjani, 2014) are lower than our result (34.30 °C). The T_{max} for the total immature stages of *Tetranychus tumidus* Banks was determined as 35.2 °C by Liu and Tsai (1998), which is close to our finding (35.44 °C). But, the reported T_{max} for *E. willamettei* was 31 °C (Stavrínides *et al.*, 2010) that is lower than our finding.

The survival rate of immature stages of *E. hirsti* was strongly affected by temperature. The Stavrínides *et al.* (2010) study showed a similar finding, reporting that the survival rate of *E. willamettei* immature stages is 30.76, 70.74, 42.28 and 62.73 % at 15, 22, 25 and 28 °C, respectively. Also, the survival of *Eotetranychus carpini* immature stages was 78, 69, 69, 71 and 48 % at 15, 19.8, 22.7, 26 and 30.3

°C, respectively that confirmed the effect of temperature on the survival rate (Bonato *et al.*, 1990). The survival of *T. urticae* immature stages was reported as 67.22 and 68.5 % on two varieties of peach at 27 °C, 50 ± 10 % RH and a photoperiod of 12L:12D (Riahi *et al.*, 2011), that are near to our finding at 25 °C (61.77 %) and 30 °C (70.59 %).

In addition to temperature, another environmental factor that greatly influences life table parameters and population dynamics of mites is relative humidity (RH). Some research discusses the relation between the RH and development of tetranychid mites (such as Kramer and Hain, 1989; Bonato *et al.*, 1995; Abou-Awad *et al.*, 2001), but there is no information about the effect of RH on the development of *E. hirsti*. Additional studies on the effects of relative humidity on the development of *E. hirsti* can further increase our knowledge to forecast its population dynamics in cropping systems. Finally, our findings suggested that the examined population of *E. hirsti* was adapted to the higher temperatures for the development of immature stages. This finding is confirmed by the distribution of this pest that is restricted to tropical zones in Iran.

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