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Effects of temperature on a Chinese population of *Amblyseius andersoni* (Acari: Phytoseiidae) fed with *Tetranychus urticae*

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Original research

ABSTRACT

The development and fecundity of *Amblyseius andersoni* (Chant) fed with *Tetranychus urticae* Koch was studied at five different temperatures (17, 20, 25, 30 and 35 °C) and life parameters of the population were calculated. The development, reproduction, longevity, and life table parameters of *A. andersoni* were significantly affected by the different temperatures. The duration of the egg, larval, protonymph, deutonymph and total immature stages were reduced when the temperature increased. The total oviposition of *A. andersoni* was highest at 25 °C and lowest at 35 °C, and the daily average oviposition increased as the temperature increased, but few eggs were laid at 17 °C. The values of the intrinsic rate of increase (r_m , 0.108–0.200), net reproduction rate (R_0 , 18.71–36.47) and the mean generation time (t , 14.68–29.73) significantly differed among the five temperatures. The highest net reproduction rate ($R_0 = 36.47$) was obtained at 25 °C. The results of this study indicated that *A. andersoni* has a high inherent potential for the control of the *T. urticae* at certain temperatures.

Keywords *Amblyseius andersoni*; *Tetranychus urticae*; temperature; population dynamics; life table

Introduction

The two-spotted spider mite, *Tetranychus urticae* Koch, is one of the most serious agricultural pests in the world. It is a polyphagous species able to feed on more than 1,100 plant species belonging to more than 250 plant families (Migeon and Dorkeld 2010). This phytophagous mite is widely distributed and is responsible for important yield losses in cultivated crops by damaging leaf tissue and sucking cell contents (Grbic *et al.* 2011; Gerson and Weintraub 2012; Meck *et al.* 2013). This pest species develops well under conditions of high temperature and low relative humidity, displaying explosive growth (Hussey and Scopes 1985). In China, *T. urticae* only occurred sporadically before the 1990's, and it spread rapidly later (Gu *et al.* 1996, Zhang and Shen 2001) and thus becomes a serious problem requiring a large use of pesticides. One explanation for this increase is that the widespread use of pesticide has eliminated natural enemies especially predatory mites (Choi *et al.* 2004, Prischmann *et al.* 2005). The challenge is thus the development of biological control strategies (Bustos *et al.* 2016).

Species of the family Phytoseiidae are the most common plant inhabiting predatory mites; they play an important role in the natural control of phytophagous mites and insects. Several phytoseiid species are commercially produced for the control of pest mites (McMurtry *et al.* 2013). Biological control of *T. urticae* with predatory mites, such as *Phytoseiulus persimilis* Athias-Henriot, has acquired special significance for a long time (Hussey and Scopes 1985, Skirvin *et al.* 2002). *P. persimilis* and *Neoseiulus californicus* (McGregor) are the subject of

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ongoing research in China, and have shown potential use in biological control of *T. urticae* (Xu *et al.* 2015, Wu *et al.* 2016). Recently, another phytoseiid mite, *Amblyseius andersoni* (Chant), was found on wild Chinese wolfberry in the city of Bayan Nur in Inner Mongolia in 2017 ; it is a new species recorded in China (Liu *et al.* 2019). *Amblyseius andersoni* a generalist phytoseiid species commonly found in apple orchards in several countries (Croft 1994, Duso and Pasini 2003), especially in Europe (Komlovszky and Jenser 1987; Hegyi *et al.* 2003, Tixier *et al.* 2014). A survey conducted in Syria, showed *A. andersoni* was a dominant species on citrus trees and on wild plants within or around orchards (Barbar, 2013). Unlike other phytoseiid mite (e.g. *N. californicus* and *P. persimilis*), adult longevity of *A. andersoni* is relatively long under experimental conditions (Amano and Chant, 1977). This predatory mite was often observed feeding on alternative foods (McMurtry 1992) and reaching high population levels (McMurtry and Rodriguez 1987). Some authors showed that, it can keep the population of spider mites under the economic threshold levels in fruit orchards (Duso 1992, Duso and Pasini 2003). The ability of *A. andersoni* to control phytophagous mites depends on several factors, such as the climatic conditions in the area (Croft *et al.* 1993), the morphological characteristics of plant leaves (Duso and Vettorazzo 1999), inter-specific competition (Duso 1989) and the impact of pesticides (Duso *et al.* 1992, Pozzebon *et al.* 2002).

Many studies have demonstrated that temperature significantly affects predatory mite performance (e.g. functional response, mating, and oviposition behaviour), and ultimately fitness (Skirvin and Fenlon 2003, Nguyen and Amano 2009, Jafari *et al.* 2010, 2012, Xia *et al.* 2012, Wang *et al.* 2014). In this paper, we studied the effects of temperature on a population of *A. andersoni* fed with *T. urticae*. The life table parameters of *A. andersoni* were also studied providing useful data for biological control applications.

Materials and methods

Mite species and populations

The *T. urticae* population used in this study was obtained from the leaves of mulberry in Salaqi, Tumut Right Banner, Baotou City, Inner Mongolia Autonomous Region (40°20'N, 110°19'E) and kept on lima bean plants in an environmental chamber at 25 ± 1 °C, 60 ± 5% RH, and L:D = 16:8. The population of *A. andersoni* was collected on Chinese wolfberry leaves in Urad Front Banner, Bayan Nur City, Inner Mongolia Autonomous Region (40°43'N, 108°39'E), in September 2017. The population was kept in laboratory on excised bean leaves heavily infested with all stages of *T. urticae* (25 ± 1 °C). The predator and prey individuals were reared for two generations before use in the experiments.

Experimental setup

Experiments were carried out in the laboratory at 25 ± 1 °C, 60 ± 5% RH, and L:D = 16:8. However, since leaflets on which the experiments were conducted were placed on water-saturated cotton we can suggest that humidity reached higher levels. Excised leaves infested with the different stages of *T. urticae* were placed dorsal side down on absorbent cotton in a large glass petri dish (12 cm in diameter and 1.5 cm in depth). The absorbent cotton was saturated with distilled water to prevent mite escape. Furthermore, the petri dish was placed on a plastic tray (40 x 35 x 2.5 cm) filled with distilled water.

For the study on developmental times, ovipositing females of *A. andersoni* were kept on detached leaflets with abundant prey. At 16 °C, eggs did not hatch, so it was impossible start the development experiments at this temperature. Therefore, experiments were carried out at 17, 20, 25, 30 and 35 °C. Eggs were removed every 6 h from the mass rearing and placed singly on detached leaflets (4 cm in diameter) which abundant prey for 30 replicates for each temperature considered. To determine the duration of the immature stages (egg, larva, protonymph and deutonymph), inspections were carried out twice a day under a stereomicroscope until the

predators reached adulthood. Also, the sex of the progeny was recorded. The leaflet was renewed once a week. Data from females which died accidentally were excluded from the analyses.

Oviposition and life table parameters

After a new generation of females emerged, the durations of preoviposition, oviposition, postoviposition, the daily fecundity and longevity of each female were recorded daily during her life. Daily age-specific survival (l_x) and fecundity (m_x) rates were calculated for each temperature with the method proposed Birch (1948).

A life table was constructed considering survival and fecundity rates for individuals. Parameters at constant temperatures were calculated as reported by Andrewartha and Birch (1954) as follows.

The net reproductive rate: $R_0 = \sum l_x m_x$

The intrinsic rate of increase: $\sum (e^{-r_m} \times l_x m_x) = 1$

The mean generation time: $t = \ln R_0 / r_m$

The finite rate of increase: $\lambda = e^{r_m}$

The doubling time: $DT = \ln 2 / r_m$

where r_m is the intrinsic rate of increase, x is female age in days, l_x is the fraction of females surviving to age x (age-specific survival rate), and m_x is the expected number of daughters produced per female alive at age x (age-specific fecundity rate), obtained by multiplying the number of eggs by the age-specific sex ratio, which is defined as the proportion of females in the progeny (Roy *et al.* 2002).

Statistical analysis

The influence of five temperatures on developmental time of immature stages, durations of preoviposition, oviposition and postoviposition, longevity and fecundity of *A. andersoni* were analyzed using one-way analysis of variance (ANOVA). When a significant difference was detected, the means were compared using Duncan's multiple ranges test. Hatchability and survival rates were compared with chi-square test using the software SPSS 19. The life table parameters of *A. andersoni* were calculated with Excel 2007 software: intrinsic rate of increase (r_m), the finite rate of increase (λ), the net reproductive rate (R_0) and the mean generation time (t).

Results

Development and survival

The developmental time of different immature stages of *A. andersoni* at five constant temperatures are presented in the Table 1. Temperature had a significant influence on eggs ($F_{4, 93} = 369.386$; $P < 0.001$), larval ($F_{4, 93} = 112.489$; $P < 0.001$), protonymphal ($F_{4, 93} = 518.669$; $P < 0.001$), deutonymphal ($F_{4, 93} = 287.256$; $P < 0.001$), and overall immature periods ($F_{4, 93} = 886.114$; $P < 0.001$) for female progeny. Egg duration decreased from 6.75 days at 17 °C to 0.79 days at 35 °C. The larval stage was the shortest for all temperatures and varied between 2.82 days at 17 °C and 0.58 day at 35 °C. The protonymphal and deutonymphal stages had almost similar durations with the deutonymphal stage slightly longer for all temperatures tested. The total immature developmental duration (egg to adult) decreased when temperature increased from 17 °C (24.71 days) to 35 °C (4.54 days). Similarly, temperature had a significant influence on egg ($F_{4, 26} = 138.230$; $P < 0.001$), larval ($F_{4, 26} = 34.919$; $P < 0.001$), protonymphal ($F_{4, 26} = 49.844$; $P < 0.001$), deutonymphal ($F_{4, 26} = 43.167$; $P < 0.001$) and overall immature periods ($F_{4, 26} = 563.898$; $P < 0.001$) for male progeny. Incubation period decreased when temperature increased from 17 °C (6.30 days) to 35 °C (1.33 days). The longest larval stage was 2.30 days

at 17 °C, and the shortest 0.50 days at 30 °C and 35 °C. The total immature developmental duration decreased from 21.70 days at 17 °C to 3.92 days at 35 °C.

Hatchability and survival rates of *A. andersoni* at five constant temperatures are presented in the Table 2. *Amblyseius andersoni* successfully developed to adulthood at all temperatures tested when fed with *T. urticae*. Temperature had a significant influence on hatchability ($\chi^2 = 17.07$; $df = 4$; $P = 0.007$) and survival rate (egg to adult) ($\chi^2 = 10.86$; $df = 4$; $P = 0.028$). The shortest hatchability and survival rates (egg to adult) were 73.33% and 63.33% at 17 °C, and the highest were 100% and 93.33% at 30 °C. However, temperature had no significant influence on survival rates in larvae ($\chi^2 = 3.75$; $df = 4$; $P = 0.440$), protonymph ($\chi^2 = 2.54$; $df = 4$; $P = 0.637$) and deutonymph ($\chi^2 = 0.09$; $df = 4$; $P = 0.999$).

Reproduction and longevity

The reproduction parameters are presented in the Table 3. Significant differences were observed for the preoviposition duration of *A. andersoni* at the five temperatures tested ($F_{4, 87} = 45.82$; $P < 0.001$); it decreased from 27.00 days at 17 °C to 0.97 days at 35 °C, gradually. The

Table 1 Developmental duration (days) of different stages of *Amblyseius andersoni* at five constant temperatures.

Temperatures	Developmental duration of <i>Amblyseius andersoni</i> (days)	
	female	male
Eggs		
17 °C	6.75±0.26a	6.30±0.30a
20 °C	3.39±0.11b	3.50±0.22b
25 °C	1.89±0.05c	1.70±0.12c
30 °C	1.55±0.06d	1.58±0.08c
35 °C	1.39±0.05d	1.33±0.11c
Larvae		
17 °C	2.82±0.19a	2.30±0.20a
20 °C	1.33±0.11b	1.30±0.20b
25 °C	0.64±0.05c	0.80±0.12c
30 °C	0.59±0.04c	0.50±0.00c
35 °C	0.50±0.00c	0.50±0.00c
Protonymph		
17 °C	6.82±0.13a	6.30±0.56a
20 °C	2.53±0.15b	2.60±0.43b
25 °C	1.75±0.07c	1.80±0.12c
30 °C	1.48±0.05d	1.42±0.08c
35 °C	1.08±0.45e	1.00±0.00d
Deutonymph		
17 °C	8.32±0.39a	6.80±0.72a
20 °C	2.78±0.16b	2.40±0.33b
25 °C	2.05±0.09c	1.80±0.25bc
30 °C	1.52±0.05d	1.58±0.08bc
35 °C	1.06±0.38e	1.08±0.08c
Total development duration		
17 °C	24.71±0.33a	21.70±0.25a
20 °C	10.03±0.18b	9.80±0.60b
25 °C	6.32±0.10c	6.10±0.29c
30 °C	5.14±0.06d	5.08±0.08d
35 °C	4.03±0.05e	3.92±0.08e

Means followed by the same letter in a column are not significantly different ($P \leq 0.05$).

Table 2 Hatchability and survival rate of immature stages of *Amblyseius andersoni* at different temperatures.

Temperature (°C)	Hatchability (%)	Survival rate in larvae (%)	Survival rate in protonymph (%)	Survival rate in deutonymph (%)	Survival rate (egg to adult) (%)
17	73.33	95.45	95.24	95	63.33
20	90	96.3	92.31	95.83	76.67
25	96.67	96.55	100	96.43	90
30	100	100	96.67	96.55	93.33
35	90	100	92.59	96	80
$\chi^2 (df=4)$	17.07	3.75	2.54	0.09	10.86
<i>P</i>	0.007	0.44	0.637	0.999	0.028

oviposition duration decreased from 30.00 days at 20 °C to 16.50 days at 35 °C, and the shortest (9.16 days) was observed at 17 °C ($F_{4, 87} = 19.22$; $P < 0.001$). The total fecundity was the highest at 25 °C (45.68 eggs) and the lowest at 17 °C (9.13 eggs) ($F_{4, 87} = 59.32$; $P < 0.001$). The daily egg production was also affected by temperature and ranged from 0.64 to 1.86 eggs/female/day ($F_{4, 87} = 53.77$; $P < 0.001$). The maximum female-biased sex ratio was 3.64: 1 (female: male) at 25 °C. The female adult longevity ($F_{4, 93} = 31.34$; $P < 0.001$) and male adult longevity ($F_{4, 26} = 6.23$; $P = 0.002$) decreased significantly with temperature increase. The female adult mites lived longer at 17 °C (40.50 days) followed at 20 °C (31.56 days), and the shortest longevity (17.31 days) was observed at 35 °C. Males had almost similar life durations as females. However, at all temperatures tested, the female adult longevity was a little longer.

The age-specific survival rate (l_x) and fecundity (m_x)

The age-specific survival rate (l_x) and fecundity (m_x) curves of *A. andersoni* at different temperatures are given in Figure 1. Age-specific survival rate started to drop at an earlier age as the temperature increased from 17 to 35 °C. The first death of an adult female occurred on day 15 at 35 °C, which is earlier than that at the other four temperatures. The curves of age specific fecundity showed that oviposition pattern varied among the temperatures, and the maximum amount of females were recorded on the 53th, 32th, 30th, 15th and 8th days at 17, 20, 25, 30 and 35 °C, respectively; and the females began to oviposit on the 25th, 15th, 9th, 8th, and 6th days at 17, 20, 25, 30 and 35 °C, respectively.

Demographic parameters

The values of life table parameters of *A. andersoni* at five constant temperatures are shown in the Table 4. Net reproductive rate (R_0) was the highest at 25 °C (36.47) and the lowest at

Table 3 Reproduction parameters of *Amblyseius andersoni* fed with *T. urticae* at five constant temperatures.

Temperature	17°C	20°C	25°C	30°C	35°C
Preoviposition duration	27.00±6.12a	7.53±0.45b	1.86±0.08c	1.39±0.06c	0.97±0.09c
Oviposition duration (days)	9.13±5.96c	30.00±1.52a	26.95±1.32a	21.18±0.59b	16.50±0.78b
Total fecundity (eggs)	9.13±4.02d	39.61±1.12b	45.68±1.61a	39.18±1.00b	27.00±1.22c
Daily fecundity (eggs/female/d)	0.64±0.15d	1.36±0.05c	1.73±0.05ab	1.86±0.03a	1.65±0.04b
Sex ratio (female/male)	2.22:1	3.45:1	3.64:1	2.34:1	2.44:1
Female longevity (days)	40.50±1.02a	31.56±1.80b	28.77±1.93b	23.68±0.84c	17.31±0.88d
Male longevity (days)	39.60±1.86a	30.80±2.44ab	27.00±7.89bc	21.17±1.62bc	15.83±1.31c

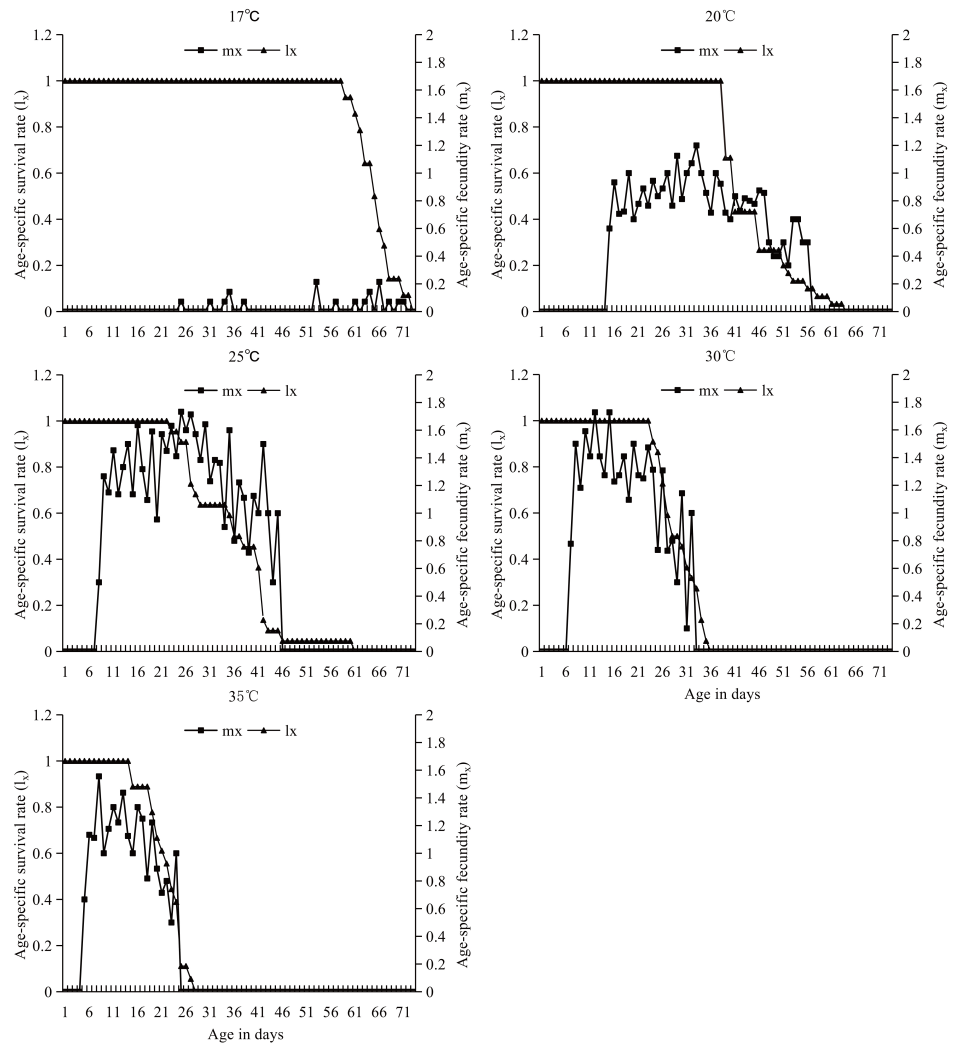


Figure 1 Age-specific survival rate (l_x) and age-specific fecundity rate (m_x) curves of female *Amblyseius andersoni* at five different temperatures. —▲— Age-specific survival rate (l_x). —■— Age-specific fecundity rate (m_x).

17 °C (1.02). When the temperature increased, the generation time of *A. andersoni* decreased gradually. The longest mean generation time was reached at 17 °C (48.16), and the shortest at 35 °C (14.68). There was a linear negative correlation between temperature and mean generation period, and the equation was $y = -1.6638x + 68.663$ ($R^2 = 0.81$, $P < 0.05$). The intrinsic rate of increase of *A. andersoni* increased gradually with increasing temperature. The lowest rate was observed at 17 °C (0.0003), and the highest at 35 °C (0.1995). Temperature and the rate of population increase were positively correlated ($y = 0.0101x - 0.1247$, $R^2 = 0.80$, $P < 0.05$). When the temperature increased, the doubling time of the population of *A. andersoni* decreased. The maximum population doubling time was obtained at 17 °C (2197.14), and the shortest at 35 °C (3.47). The lowest finite rate of increase was at 17 °C (1.000), and the highest at 35 °C (1.221). The relationship between temperature and finite rate of increase was linear ($y = 0.011x + 0.856$, $R^2 = 0.82$, $P < 0.05$).

Table 4 Parameters of life table of *Amblyseius andersoni* at five constant temperatures.

Parameter	Temperature				
	17 °C	20 °C	25 °C	30 °C	35 °C
Net reproductive rate (R_0)	1.02	25.09	36.47	27.85	18.71
Mean generation time in days (t)	48.16	29.73	22.4	17.04	14.68
Intrinsic rate of increase (r_m)	0.0003	0.1083	0.1606	0.1951	0.1995
Population doubling time in days (DT)	2197.14	6.4	4.32	3.55	3.47
Finite rate of increase (λ)	1	1.114	1.174	1.216	1.221

Discussion

Our results revealed that temperature significantly affected the developmental time of *A. andersoni*, and that this predator could successfully develop under a wide range of temperatures from 17 to 35 °C. Total developmental time of *A. andersoni* recorded by Amano and Chant (1977) fed on *T. pacificus* at 23 °C (7.43 days) is close to our finding at 25 °C (8.18 days).

The preoviposition periods and female longevity of *A. andersoni* shortened as the temperature increased, showing a similar trends as reported by Amano and Chant (1977) although the specific values (1.86) obtained in the present study was different from the reported value (2.14). The oviposition rate of *A. andersoni* was low at low temperatures, and only a few individuals laid eggs at 17 °C. The reason for this might be that the predator entered reproductive diapause at low temperatures (Van Houten *et al.* 1988). Genini *et al.* (1991) reported that the daily egg production of *A. andersoni* fed on *T. urticae* was 1.76 at 20 °C, which was higher than the value (1.36) in the present work. The reason for this may be from different geographic populations of the predator species considered.

The sex ratio of phytoseiids is generally female biased and varies within and between species, but poor prey conditions may reduce the proportion of females (Friese and Gilstrap 1982, Sabelis 1985a,b, Ganjisaffar *et al.* 2011). In our experiments the sex ratio of *A. andersoni* was female biased at five constant temperatures, but the maximum sex ratio was found at 25 °C. Sabelis and Nagelkerke (1988) revealed that at low temperatures a pseudo-arrhenotoky process led to production of higher number of sons. Our results suggested that this phenomenon in *A. andersoni* could occur not only at low temperatures, but also at higher temperatures.

The intrinsic rate of increase (r_m) is a key demographic parameter useful for predicting the population growth potential of an animal under given environmental conditions (Andrewartha and Birch 1954). Our results showed that, like other phytoseiid mites, the r_m value of *A. andersoni* is affected by temperature. At 17 °C, the lower r_m value was due to low values of fecundity and survival rate, low production of female offspring in the population, and long life span. At 20 °C, fecundity and survival rate increased, but the r_m value was still lower compared to that at the other higher tested temperatures. We concluded that the long life span at 20 °C led to a low value of r_m . Genini *et al.* (1991) found that the r_m of *A. andersoni* fed on *T. urticae* was 0.151 at 20 °C, which was higher than the value obtained (0.108) in the present work. This difference may be due to differences in geographic populations. At temperatures above 20 °C, it seems that the shorter life span of females is the major reason for increasing r_m . Our results showed that the main effect of temperature on r_m value of *A. andersoni* was mostly due to effect on developmental time of the predator. The present study indicated that the maximum r_m value of *A. andersoni* was obtained at 35 °C, which showed this predator seems to be a thermophile species, even though the highest value of survival and fecundity was at 25 °C and 30 °C, respectively.

Finally, although our results indicated that the population of *A. andersoni* was limited by low temperature, *A. andersoni* has a high inherent potential for the control of the *T. urticae*, especially at a temperature range of 30–35 °C. Therefore further experiments on the life table

of the local population of *T. urticae*, under more realistic circumstances, are needed in order to get a better understanding of its efficiency for a successful biological control of *T. urticae*.

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