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Temperature influences the development, survival, and life history of *Axinoscymnus apioides* Kuznetsov & Ren (Coleoptera: Coccinellidae), a predator of whitefly

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Abstract: The current work was aimed at studying the biology of *Axinoscymnus apioides* Kuznetsov & Ren (Coleoptera: Coccinellidae) under different temperature regimes. These studies were performed at 6 constant temperature regimes (17, 20, 23, 26, 29, and 32 °C) under laboratory conditions in which *A. apioides* was fed with *Bemisia tabaci* Gennadius (Hemiptera: Aleyrodidae) nymphs on *Hibiscus rosa-sinensis* plants. Results indicated that the developmental period for different immature stages decreased with increases in temperature from 17 to 29 °C. The developmental periods of first instar larvae and pupae decreased, while those of second, third, and fourth larval instars increased for the temperature regimes above 29 °C. The survival rates of different larval stages were almost stable at temperatures ranging between 20 and 32 °C. The highest fecundity of *A. apioides* females (307.80 eggs) was recorded at 23 °C. Based on these results, life tables of *A. apioides* were constructed for temperatures in the range of 17–29 °C. The innate capacity for increase (r_m), the finite rate of increase (λ), and the reproductive rate (R_0) reached maximum at 26 °C. The mean length of a generation (T) decreased with increasing temperatures. The lower development thresholds of *A. apioides* for the total preimaginal development was 9.21 °C, whereas the number of degree-days required for development from egg to adult emergence was 344.83 degree days. The results indicated that the optimal temperature range for *A. apioides* ranged between 23 and 26 °C.

Key words: *Axinoscymnus apioides*, temperature, development, fecundity, life table

1. Introduction

The sweet potato whitefly, *Bemisia tabaci* Gennadius (Hemiptera: Aleyrodidae), is a major pest of economically important crops worldwide (Cuthbertson, 2013). In China, it has been affecting major crops since 1990, resulting in huge losses every year (He et al., 2013). More recently, *B. tabaci* populations have been suppressed by using various classes of insecticides, such as organophosphates, carbamates, pyrethroids, and neonicotinoids (Liang et al., 2012). However, it has been reported that *B. tabaci* is difficult to control with both conventional and newer insecticides because of the rapid development of resistance (Zheng et al., 2012). Thus, the best course of action may be biological control combined with other pest control methods. Whiteflies have many natural enemies, and whitefly outbreaks frequently occur when natural biological control is disrupted. Therefore, biological control or integrated pest management should be considered as an option for controlling this pest. Many

attempts at controlling whitefly by using natural enemies have been successful (Yao et al., 2010). The insect predators being used for whitefly management include *Serangium parcesetosum*, *S. japonicum*, *Nephaspis oculatus*, *Cliostethus artuatus*, and *Delphastus catalinae* (Liu and Stansly, 1999; Ren et al., 2002; Simmons and Legaspi, 2004).

Studies regarding biological control of *B. tabaci* in different regions of the world have indicated that coccinellid predators belonging to the genus *Axinoscymnus* (Coleoptera: Coccinellidae) consistently perform best in the field as well as under laboratory conditions (Ren and Pang, 1992; Huang et al., 2003, 2006, 2008). *Axinoscymnus apioides* is native to Southeast Asia; this species was first reported by Kuznetsov and Ren (1991). The morphological characteristics and biology of *A. apioides* feeding on *B. tabaci* were described by Wang et al. (2006); however, the influence of different factors (temperature, host plants) on the reproductive biology of *A. apioides* has not been well studied. The objective of our study was to

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observe the influence of temperature on the development, reproduction, and life table parameters of *A. apioides* when fed on different life stages of *B. tabaci*.

2. Materials and methods

2.1. Plant materials

Hibiscus rosa-sinensis was grown in 15-cm plastic pots. Sufficient slow-release fertilizer (N:P:K = 13:7:15, Batian Ecotypic Engineering Co., Ltd., Xili, Shenzhen, China) was added as needed to maintain normal plant growth.

2.2. Insects

A. apioides and *B. tabaci* were reared on *Hibiscus rosa-sinensis* in a greenhouse. *B. tabaci* and *A. apioides* were reared on *H. rosa-sinensis* for more than 10 generations before their use in these studies. Laboratory studies were conducted in an air-conditioned room at 25 ± 2 °C and $80 \pm 5\%$ RH with a photoperiod of 14:10 (L:D).

2.3. Effect of temperature on development and survivorship of immature *A. apioides*

Adult beetles collected from the stock culture in the greenhouse were fed on *B. tabaci* and maintained on *H. rosa-sinensis* plants for oviposition. Leaves bearing beetle eggs less than 12 h old were then confined in clear plastic petri dishes (9 cm in diameter) lined with a moist filter paper (8 cm in diameter) to prevent desiccation of the eggs. The petri dishes were then placed in growth chambers (PXY-300QA, Shaoguan Keli Experimental Instrument Co., Ltd., Shaoguan, Guangdong, China) at 6 temperature regimes (17, 20, 23, 26, 29, and 32 ± 1 °C), a relative humidity of $75 \pm 10\%$, and a photoperiod of 14 h L:10 h D. This temperature range covers diverse geographical regions that might influence the physioecological activities of the predator. Cohorts of at least 60 eggs were selected for each treatment, with 3 replicates; eggs were monitored daily until all had hatched. The neonates were gently removed from the leaves and transferred using a fine brush (No. 00) to fresh leaf disks of *H. rosa-sinensis* leaves (10–15 cm²) bearing immature *B. tabaci* in a petri dish. Leaf disks were replaced daily except during the pupal stage. Developmental times and mortality of each development stage through adult eclosion were recorded.

2.4. Effect of temperature on longevity and fecundity of *A. apioides* adults

To evaluate longevity and other biological parameters, newly emerged adults were individually placed on a leaf disk infested with *B. tabaci* eggs. After mating, a total of 15 randomly selected pairs were placed separately on a leaf disk 5–8 cm wide with a moistened filter paper lining the bottom of a petri dish. Petri dishes were placed in growth chambers with the same settings as above. Fresh leaf disks with whitefly eggs were provided daily as a source of food. The numbers of eggs oviposited, surviving adults,

and longevity of *A. apioides* were recorded daily until all beetles died. The sex of each adult was determined after death by dissecting and exposing the reproductive organs.

2.5. Life table analysis

A cohort of X eggs laid at an interval of 24 h was counted and monitored until the appearance of adults. This gave information on age-specific survivorship. Twelve pairs of adults were then monitored daily to gain insight into age-specific fecundity. The life table parameters were computed according to Birch (1948):

$$R_0 = \sum L_x M_x,$$

$$T = 1 / R_0 \sum L_x M_x,$$

$$r_m = \ln R_0 / T,$$

$$\lambda = \exp(r_m),$$

where x is the age in days of *A. apioides*, L_x is the survivorship at time x, M_x is the number of female eggs (according to the sex ratio) laid per female and per day, T is the mean generation time, R_0 is the net reproductive rate, and r_m is the intrinsic rate of increase.

2.6. Estimation of lower development threshold and sum of effective temperature

The lower development threshold (LDT) and the sum of effective temperatures (SET) were estimated using the development times of the preimaginal stages at each constant temperature. It was assumed that within the interval of temperatures favorable for the insects' development, the relationship between the inverse of the development time (development rate) and the temperature is nearly linear (Honek and Kocourek, 1990). According to this, the following linear relationship was considered:

$$1 / D = aT + b,$$

where D corresponds to the development time of the preimaginal, which is inversely proportional to the temperature (T), while a and b are the regression parameters.

The SET [degree-days (°D)] was calculated according to the following expression:

$$SET = [D_{T_1} (T_1 - LD_{T_1}) + \dots + [D_{T_n} (T_n - LD_{T_n})] / n$$

where D_{T_1} is the development time at temperature T_1 , and D_{T_n} is the development time at temperature T_n .

LD_{T_1} is the lower development threshold for the temperature T_1 , and LD_{T_n} is the lower development threshold for the temperature T_n . n is the total number of temperature regimes used in this study.

2.7. Statistical analysis

To correct for heteroscedasticity, data regarding preimaginal development time, adult longevity, and preoviposition and oviposition periods were transformed by log (x), and fecundity data by log (x + 1), prior to analysis of variance (ANOVA) (Hill and Hill, 2002). Where statistical differences existed between data sets ($P < 0.05$), Tukey's HSD test was used to separate the differing means. Accumulated survival rates (from egg to adulthood) were

analyzed by multiple comparison tests for proportions (Zar, 1996). All analyses were performed with SAS 8.01 for Windows (SAS, 2000). The values displayed are regular averages and standard errors.

3. Results

3.1. Effect of temperature on development and survivorship of immature *A. apioides*

Temperature had a significant effect on the developmental period of *A. apioides* eggs; these differences were more notable at lower temperature regimes, ranging from 17 to 23 °C (Table 1). Subsequently, the total developmental period (from egg to adult) was almost three times longer at 17 °C than that observed at 32 °C. Generally, the developmental periods of eggs; first, second, third, and fourth larval instars; pupae; and egg–adult decreased with an increase in temperature from 17 to 29 °C (Table 1). However, above 29 °C, the development periods of first instar larvae and pupae decreased while those of second, third, and fourth larval instars increased.

Temperature also had a significant effect on survivorship percentage for all *A. apioides* larval instars (Table 2). The survival rates of different larval stages were almost stable at temperatures ranging between 20 and 32 °C. Below 20 °C, the survivorship of larval instars and pupae declined significantly. Of the 7 developmental stages, survivorship of eggs was lower compared to that of second, third, fourth, and pupal instars (Table 2). Overall percentage of survivorship from egg to adult varied from 0.2 at 17 °C to 0.69 at 26 °C.

3.2. Effect of temperature on longevity, preovipositional period, oviposition, and sex ratio of *A. apioides*

The effect of temperature on longevity, preoviposition period, fecundity, and sex ratios of *A. apioides* adults differed significantly among the tested temperatures (Table 3). Average longevity varied from 202.9 days at 20 °C to 47.5 days at 32 °C. The sex ratio was also significantly influenced by different temperature regimes. The lowest sex ratio was observed at 32 °C, with the highest value at 26 °C. The highest fecundity of *A. apioides* females (307.80 eggs) was recorded at 23 °C. The longest preoviposition period (13.6 days) was observed at 20 °C, while the shortest (9.7 days) was recorded at 26 °C.

3.3. Effect of temperature on age-specific survivorship and fecundity of *A. apioides*

Independent of temperature and age, the age-specific survival curve of females (l_x) showed a constant rate of mortality corresponding to a typical type II hypothetical survivorship curve (Figure). The natality (m_x) differed among all temperatures: at 20 °C, the females maintained a constant and low rate of larvae production, while at 23 °C and 26 °C the number of expected larvae peaked during the first 15 days of their lives; a fluctuation in these peaks was observed throughout their life periods (Figure).

The influence of temperature (T) on oviposition (Y) can be described by the following equation:

$$Y = -2.7444 + 0.2570T - 0.0049T^2 \quad (r = 0.8955, P < 0.05).$$

3.4. Effect of temperature on life table parameters

The innate capacity for increase (r_m) and the finite rate of increase (λ) reached a maximum at 26 °C, with values

Table 1. Means (±SE) of developmental time (in days) of different stages of *A. apioides* at 6 constant temperatures.

Life stages	Temperature (°C)						F; df; P
	17	20	23	26	29	32	
Egg	10.82 ± 0.12 a	8.04 ± 0.02 b	5.38 ± 0.39 c	4.70 ± 0.33 d	3.60 ± 0.04 e	4.05 ± 0.01 e	109.42; 5; <0.0001
1st instar larvae	5.47 ± 0.18 a	4.13 ± 0.03 b	2.77 ± 0.08 c	2.47 ± 0.17 cd	2.17 ± 0.07 de	1.90 ± 0.06 e	87.62; 5; <0.01
2nd instar larvae	4.52 ± 0.11 a	3.43 ± 0.24 b	2.17 ± 0.11 c	1.81 ± 0.08 d	1.41 ± 0.01 e	1.64 ± 0.05 de	104.19; 5; <0.0001
3rd instar larvae	4.89 ± 0.01 a	3.34 ± 0.16 b	2.03 ± 0.10 c	1.74 ± 0.07 d	1.22 ± 0.01 e	1.71 ± 0.02 d	88.93; 5; <0.001
4th instar larvae	6.01 ± 0.05 a	4.33 ± 0.05 b	2.97 ± 0.07 c	2.75 ± 0.24 cd	2.56 ± 0.12 d	2.72 ± 0.02 cd	93.87; 5; <0.0001
Pupae	17.40 ± 1.63 a	12.89 ± 0.27 b	8.38 ± 0.07 c	7.50 ± 0.14 cd	6.07 ± 0.09 de	5.38 ± 0.02 e	94.34; 5; <0.0001
Total	48.78 ± 1.59 a	36.25 ± 0.03 b	23.10 ± 0.05 c	21.66 ± 0.19 c	17.00 ± 0.34 d	17.20 ± 1.12 d	132.77; 5; <0.001

Means in each row followed by the same letters are not significantly different (Tukey’s test, P < 0.05). Total refers to the developmental time of *A. apioides* from egg to adult emergence.

Table 2. Means (\pm SE) of survivorship of different stages of *A. apioides* at 6 constant temperatures.

Life stages	Temperature ($^{\circ}$ C)						F; df; P
	17	20	23	26	29	32	
Egg	0.64 \pm 0.03 b	0.67 \pm 0.08 b	0.71 \pm 0.11 b	0.88 \pm 0.01 a	0.65 \pm 0.07 b	0.68 \pm 0.06 b	23.47; 5; <0.0001
1st instar larvae	0.82 \pm 0.10 a	0.90 \pm 0.02 a	0.86 \pm 0.06 a	0.93 \pm 0.01 a	0.95 \pm 0.04 a	0.94 \pm 0.01 a	15.19; 5; <0.01
2nd instar larvae	0.88 \pm 0.07 b	0.98 \pm 0.03 a	0.96 \pm 0.02 ab	0.97 \pm 0.02 a	1.00 \pm 0.00 a	0.94 \pm 0.01 a	14.32; 5; <0.0001
3rd instar larvae	0.95 \pm 0.04 a	1.00 \pm 0.00 a	0.95 \pm 0.02 a	1.00 \pm 0.00 a	0.97 \pm 0.00 a	0.92 \pm 0.05 a	11.77; 5; <0.001
4th instar larvae	0.65 \pm 0.11 b	0.91 \pm 0.03 a	0.94 \pm 0.02 a	0.93 \pm 0.01 a	0.97 \pm 0.00 a	0.91 \pm 0.03 a	10.67; 5; <0.0001
Pupae	0.65 \pm 0.11 b	0.91 \pm 0.03 a	0.94 \pm 0.02 a	0.93 \pm 0.01 a	0.97 \pm 0.02 a	0.91 \pm 0.03 a	14.21; 5; <0.0001
Adult	0.20 \pm 0.06 c	0.48 \pm 0.01 b	0.49 \pm 0.00 b	0.69 \pm 0.02 a	0.57 \pm 0.06 ab	0.46 \pm 0.02 b	13.45; 5; <0.001

Means in each row followed by the same letters are not significantly different (Tukey’s test, $P < 0.05$).

Table 3. Mean (\pm SE) preovipositional period, oviposition, longevity, and sex ratios of *A. apioides*.

Temp. ($^{\circ}$ C)	Preovipositional period (days)	Oviposition (eggs/female)	Female longevity (days)	Sex ratio (F / M + F)
20	13.60 \pm 0.67 a	92.00 \pm 3.13 cd	202.90 \pm 23.48 a	0.53 \pm 0.2 c
23	10.50 \pm 0.45 b	307.80 \pm 25.40 a	151.00 \pm 4.92 b	0.55 \pm 0.5 b
26	9.70 \pm 0.22 b	236.20 \pm 17.66 ab	108.30 \pm 23.70 bc	0.58 \pm 0.3 a
29	10.50 \pm 1.57 b	165.91 \pm 14.53 bc	94.50 \pm 6.71 cd	0.48 \pm 0.3 d
32	13.10 \pm 1.12 a	18.50 \pm 2.68 d	47.50 \pm 8.27 d	0.42 \pm 0.1 e
F; df; P	76.74; 5; <0.0001	72.87; 5; <0.0001	59.47; 5; <0.0001	25.72; 5; <0.0001

Means in the same column followed by the same letter are not significantly different (Tukey’s test, $P < 0.05$).

of 0.062 and 1.064, respectively; their values decreased at higher and lower temperatures (Table 4). For the reproductive rate (R_0), the maximum value was 81.49 at 26 $^{\circ}$ C. The mean length of a generation (T) decreased with increasing temperature. The results indicated that the optimal temperature range for *A. apioides* was 23–29 $^{\circ}$ C.

3.5. Lower development threshold and sum of effective temperatures for *A. apioides* development

Within the range of temperatures tested, the LDT ($^{\circ}$ C) and the SET ($^{\circ}$ D) for *A. apioides* were effectively determined by a linear model, as shown by the high coefficients of determination obtained for all developmental stages (all $R^2 > 0.90$) (Table 5). The lower development thresholds of *A.*

apioides life stages ranged from 8.67 $^{\circ}$ C (egg stage) to 10.08 $^{\circ}$ C (pupae); for total preimaginal development, it was 9.21 $^{\circ}$ C (Table 5).

The number of degree-days required for the development of each preimaginal stage ranged from 29.59 $^{\circ}$ D (third larval stage) to 116.28 $^{\circ}$ D (pupa); to complete the development from egg to adult emergence required 344.83 $^{\circ}$ D (Table 5).

4. Discussion

The success and establishment of any insect population is dependent upon various environmental factors such as temperature and humidity (van Lenteren et al., 2006). This

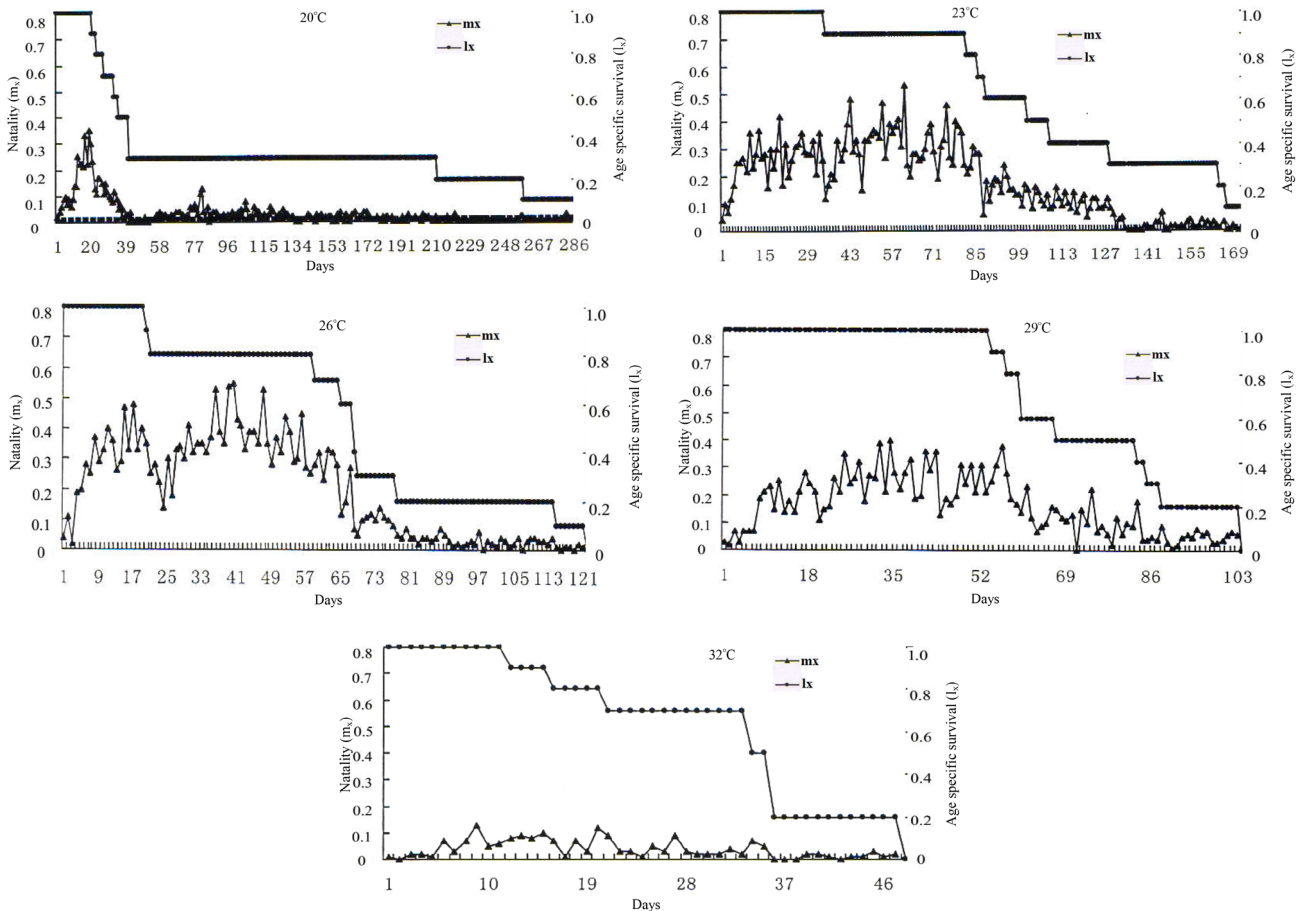


Figure. Age-specific survival rate (l_x) and natality (m_x) of *Axinoscyrmus apioides* at different temperatures (20 °C, 23 °C, 26 °C, 29 °C, and 32 °C).

Table 4. Mean (\pm SE) life table parameters of *A. apioides* at different temperatures.

Temp. (°C)	N	Intrinsic rate of increase (r_m)	Net reproductive rate (R_0)	Generation time (T)	Finite rate of increase (λ)
20	15	0.027	22.80	115.96	1.027
23	15	0.046	75.41	93.35	1.047
26	15	0.062	81.49	70.94	1.064
29	15	0.056	47.28	69.43	1.057
32	15	0.030	4.26	47.59	1.031

study was carried out to explain the effects of temperature on survival and development of *A. apioides* for importation and release into new environments to control *B. tabaci* under field and greenhouse conditions.

Results of this study revealed that a temperature range between 23 °C and 29 °C was optimal for growth and development of *A. apioides*. These results are similar to the findings of Yao et al. (2010), who explained effects of temperature on growth and development of *Serangium*

japonicum (Coleoptera: Coccinellidae) and observed that temperatures between 23 and 29 °C were optimal for growth and development. Our results are different from those of Huang et al. (2008), who observed an optimal temperature range of 20–26 °C for growth and development of another coccinellid, *A. cardilobus*.

Our results showed that *A. apioides* has an intrinsic rate of increase (r_m) of 0.062 at 26 °C when fed on immature stages of *B. tabaci*. This value was different from those

Table 5. Lower development threshold (LDT) and sum of effective temperatures (SET) required for the development of the different life stages of *A. apioides*, with the respective coefficient of determination (R^2), slope (a), and intercept (b).

Life stages	dT = a Temperature + b		R^2	LDT (°C)	SET (°D)
	a	b			
Egg	0.0120	-0.1040	0.94	8.67	83.33
1st instar larvae	0.0233	-0.2100	0.98	9.01	42.92
2nd instar larvae	0.0314	-0.2967	0.97	9.45	31.85
3rd instar larvae	0.0338	-0.3333	0.93	8.86	29.59
4th instar larvae	0.0143	-0.0400	0.91	2.80	69.93
Pupae	0.0086	-0.0867	0.98	10.08	116.28
Egg-adult	0.0029	-0.0267	0.96	9.21	344.83

reported for other ladybird beetles (*Nephaspis oculatus*, *A. cardilobolus*, *Stethorus picipes*, *S. japonicum*) fed on *B. tabaci* at the same temperature (Tanigoshi and McMurtry, 1977; Ren et al., 2002; Huang et al., 2008; Yao et al., 2010). The differences in the intrinsic rate of increase of these predators can be attributed to certain factors such as the diets of prey and their host plants, and the sex ratios of the predators.

The lower threshold for development and sum of effective temperatures are useful indicators of the potential distribution of an insect (Huang et al., 2008). Our findings show that a threshold temperature of 9.21 °C and 344.83 degree-days are required for *A. apioides* to complete one generation. This clearly suggests that *A. apioides* has the ability to remain active at low temperatures in most temperate regions if temperatures inside greenhouse systems fall between 14 and 18 °C during winter. The biological fitness of *A. apioides* was significantly minimized at 20 °C during this study. *A. apioides* also survived until adult emergence, although the proportion was significantly different at different temperatures. These results are different from the findings of Yao et al. (2010), who showed a lower development threshold of 9.41 °C and the sum of effective temperature of 285.71 degree days for *S. japonicum*.

The synchronization of any natural enemy's life cycle with its prey is an important attribute. Optimum fecundity and other demographic parameters of *A. apioides* occurred at temperatures of 23–26 °C. Similarly, Butler et al. (1983) reported that the maximum fecundity of *B. tabaci*

occurred at 26.7 °C. These values suggest that predator and prey would seem to share the same optimum temperature, a desirable attribute for the former to suppress *B. tabaci* populations. It also suggests that *A. apioides* is an ideal candidate for biological control of *B. tabaci* populations in tropical regions under field conditions and in temperate regions under greenhouse conditions.

Our research was designed to investigate the effects of temperature on the biology and life history of *A. apioides*. This information can be useful not only for commercial rearing of this predator but also for determining the influence of climatic conditions on the efficacy of *A. apioides* as a biological control agent against *B. tabaci*. Our results have shown that *A. apioides* exhibits sufficient environmental plasticity to be a useful biological control agent against *B. tabaci* under a wide range of temperature conditions.

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