Biological characteristics, functional and numerical responses of the predatory mite *Amblyseius swirskii* (Acari: Phytoseiidae) feeding on cotton whitefly, *Bemisia tabaci* (Hemiptera: Aleyrodidae)

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Abstract. *Amblyseius swirskii* Athias-Henriot has attracted substantial attention as a biological control agent. The life history traits and functional and numerical responses of *A. swirskii* fed on *Bemisia tabaci* (Gennadius) were studied under laboratory conditions (25±2°C, 60±5% RH and 16 L: 8D). The immature developmental time, survival, and fecundity of *A. swirskii* were evaluated by putting its fresh eggs on cucumber leaf disks (2.5 cm diameter) infested with different immature stages of *B. tabaci*. Results showed that the predatory mite could feed and complete its development on both *B. tabaci* eggs and 1st instar nymphs. Total preadult developmental period of female *A. swirskii* fed on eggs and 1st instar nymphs of *B. tabaci* were 5.62 and 5.12 days, respectively. The sex ratio (female percentage) of *A. swirskii* feeding on the above diets were 70 and 72 %, respectively. Female longevity of *A. swirskii* fed on above mentioned diets was 25.27 and 26.97 days, respectively, and total fecundity were 47.20 and 41.70 eggs, respectively. The intrinsic rate of increase (r_m) of *A. swirskii* fed on above mentioned diets were 0.2040 and 0.1863 day^{-1}, respectively. By using the logistic regression, a type II functional response for feeding *A. swirski* on different densities (5, 10, 20, 30, 45, and 60) of *B. tabaci* eggs was determined. The highest mean number of preys fed by a single female *A. swirskii* was 38.50 and 34.70 eggs recorded at densities of 60 and 45 preys, respectively, with no significant difference. Searching efficiency (*a*) and handling times (T_h) of the female mites were estimated as 0.1056 h^{-1} and 0.3534 h, according to nonlinear least-square regression. The maximum theoretical predation (T/T_h) for female mites was 67.91eggs/day. In terms of eggs laid, the reproductive numerical response showed no significant difference with increasing prey density. Overall, the results of the present study indicated that *A. swirskii* has a good potential to control *B. tabaci*. Therefore, further glasshouse and field research is warranted.

Keywords: Attack rate, Fecundity, Handling time, Life table, Prey density

Introduction

The cotton whitefly, *Bemisia tabaci* Gnnadius (Hemiptera: Aleyrodidae), is one of the most important crop pests that cause damage to a large number of agricultural and greenhouse plants in Iran and the world (Behdad, 1983; Byrne & Bellows, 1991; Gerling & Mayer, 1996; Khanjani, 2004). This polyphagous insect is distributed in America, Europe, Africa, Asia, and Australia (Russel, 1975; Gerling & Mayer, 1996) and has been registered on more than 506 host plant species (Fishpool & Burban, 1994). Fifty percent of such host plant species belong to the five families Fabaceae, Asteraceae, Malvaceae, Solanaceae, and Euphorbiaceae (Mound & Hasley, 1978;

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Fishpool & Burban, 1994). In Iran, *B. tabaci* has many hosts of ornamental plants, field crops, and weeds (Habibi, 1975; Monsef & Kashkouli, 1987). The agricultural hosts of this pest include cotton, eggplant, tomato, sesame, hemp, sunflower, and cucurbit plants (Monsef & Kashkouli, 1987; Khanjani, 2004). This insect has also been reported on fruit trees such as grapevine, citrus, pomegranate, fig, and mulberry (Salavatian, 1988; Khanjani, 2004). Today, there is concern that outbreaks of *B. tabaci* may lead to serious reductions in food and fiber production in tropical and subtropical regions (Butler *et al.*, 1989; Gerling & Mayer, 1996; Thompson, 2011; Smith, 2017).

Bemisia tabaci damages plants differently; direct damage includes sucking plant sap, and indirect damage includes honeydew secretion and transmission of viral diseases. Sucking plant sap reduces the potency of the plant and may lead to the death of the plant (Butler *et al.*, 1989; Gerling & Mayer, 1996; Khanjani, 2004; Polston *et al.*, 2014).

Currently, the most important control method for *B. tabaci* is the using insecticides. On the other hand, it is very difficult to control *B. tabaci* with chemicals because the adult insects, as well as the immature growth stages of this pest, are located on the underside of the leaf and, as a result, the insecticides will not be in direct contact with them (Prabhaker *et al.*, 1985). In addition, resistance to various insecticides and growth regulators has been reported for *B. tabaci* (Prabhaker *et al.*, 1985; Cahill *et al.*, 1995, 1996; Castle & Prabhaker, 2013; Bass *et al.,* 2015; Smith *et al.,* 2016). Furthermore, the use of pesticides affects natural enemies and leads to environmental pollution. Therefore, extensive research has been performed to find effective natural enemies, including predators, parasitoids, and fungal pathogens, and as a result, several species were identified and their biological characteristics were studied (Gerling, 1990a). Among the parasitoids, the wasps belonging to the Aphelinidae family are considered this pest's most important group of parasitoids. Another group of natural enemies of *B. tabaci* are predators, such as Coccinellidae and Chrysopidae (Gerling, 1990b; Gerling & Mayer, 1996). In addition, the mites belonging to the family Phytoseiidae have also been reported as important predators of the cotton whitefly (Gerling, 1990a, b; Nomikou *et al.,* 2001; Gerling *et al.,* 2001; Calvo *et al.,* 2011; Barbosa *et al.,* 2019). Phytoseiids are the most well-known predatory mites and have been studied the most due to their success in controlling spider mites, other mite species, thrips, and whiteflies. These predators move quickly and actively search for prey and feed mainly on mites, as well as small insects, nematodes and fungi (Gerson *et al.,* 2003; McMurtry *et al.,* 2013). *Amblyseius swirskii* Athias-Henriot is a beneficial predatory mite endemic to the eastern Mediterranean region. This species is considered a generalist predator and readily consumes small soft-bodied arthropod pest species and pollen or plant exudates. As Calvo *et al.* (2015) noted, *A. swirskii* has attracted substantial interest as a biological control agent of mites, thrips, and whiteflies in greenhouse and nursery crops and is currently reared and sold commercially in Europe, North America, as well as Iran for this purpose.

Little information is available with regard to the predatory characteristics of *A. swirskii* feeding on *B. tabaci* in Iran and the world; only one study has evaluated the functional response of *A. swirskii* on *B. tabaci* (Nawar & Imam, 2019) and no data is available with regard to the numerical response of *A. swirskii* feeding on *B. tabaci*. It should be noted that although Nawar & Imam (2019) studied the functional response of *A. swirskii* on *B. tabaci,* however, it has been reported that different strains of phytoseiid species have shown different biological characteristics (Hassan, 1982; Perring & Lackey, 1989; Gough, 1991). Thus, the current study enhances our knowledge of the life history and functional and numerical response of *A. swirskii* fed on *B. tabaci*.

Materials and methods

Amblyseius swirskii rearing

Amblyseius swirskii individuals were purchased from Abadagrico, Hamedan, and reared at Shahid Chamran University of Ahvaz in rearing units and fed with date palm pollen. Our previous experiment indicated that date palm pollen is a suitable diet to maintain *A. swirskii* population in laboratory conditions (Rahmani Piyani *et al.,* 2021). The rearing units consisted of Petri dishes (90 mm dia.) on the bottom of which a piece of sponge with dimensions of 4× 4 × 1 cm was placed. A square green plastic sheet four centimeters long was placed on the sponge. Two-cm-wide strips of tissue paper were placed on the edges of the plastic sheet, one centimeter of the

width of the tissue paper was placed on the upper edge of the plastic sheet, and the remaining of it was hanging in the water inside the Petri dish to wet tissue paper and create a barrier around the plastic sheet.

Five to six males and females of *A. swirskii* mites were placed inside each of these rearing units on the plastic sheet with some date pollen for feeding. A two-centimeter-long black thread was placed on the plastic sheet (Riahi *et al.*, 2017). Females laid their eggs on these threads, which resemble veins of plant leaves.

In order to strengthen the *A. swirskii* predator mite colony growth, some strawberry spider mites, *Tetranychus turkestani* Ugarov and Nikolski, which were reared on cowpea (*Vigna unguiculata* (L.) Walp.) (Mashhad cultivar) were added to the diet of the *A. swirskii* predator mite every two months. The laboratory conditions at growth chambers were 25±2 °C, 60±5% RH, and 16:8 h (L:D).

B. tabaci colony

Cucumber (*Cucumis sativus* L.) seeds (Negin cultivar) were planted in pots (20 cm d. 25 cm ht.) filled with peat moss, compost, and perlite and kept in a growth chamber (25±2 °C, 60±5% RH, and 16:8 h (L:D)) at Shahid Chamran University of Ahvaz. When the cucumber plants were in the four-leaf stage, they were transferred into a wooden cage of 120 × 60 × 60 cm and kept in laboratory conditions (25±2 °C, 60±5% RH, and 16:8 h (L:D)). 20-30 adult whiteflies (male and females) were collected from cucumber plants grown in glasshouses of the Faculty of Agriculture, Shahid Chamran University of Ahvaz, by using an aspirator and placed on the lower surface of a cucumber leaf, using a clip cage. After 24 hours, the clip cage was removed to let the initial population of whiteflies establish on cucumber plants. After about a month, the whitefly colony was established. Whitefly was identified as *Bemisia tabaci* (Gennadius) (Bink-Moenen, 1983).

Biological characteristics and life table parameters of *A. swirskii*

Experimental conditions

The experimental units included a Petri dish (90 mm dia.), inside of which there was a round piece of agar (30 mm dia.) (Heydari *et al.*, 2016). A round piece of cucumber leaf (25 mm dia.) was placed on the agar in such a way that the lower surface of the cucumber leaf carrying eggs or nymphs of *B. tabaci* was placed on the top. Using an incubator, the experiment was conducted at 25±2 °C, 60±5% RH, and 16:8 h (L:D).

Life table study

A. swirskii eggs deposited within a 24-h period were obtained from the stock colony and maintained for one generation by feeding on eggs and different nymphal stages of *B. tabaci*. At this stage, newly laid *A. swirskii* eggs (less than 24 hours old) were caged individually into an experimental unit. Each treatment was replicated 30 times. When the larval stage of *A. swirskii* emerged, eggs and different nymphal stages (First to fourth nymphal stage) of *B. tabaci* were supplied at overabundance to each larva on a piece of cucumber leaf placed on a layer of agar. Preadult developmental duration and survival rate of *A. swirskii* were recorded daily. After the emergence of adult *A. swirskii*, females and males were paired and kept together in rearing units with the same diet of the preadult stage. Adult longevity, fecundity, and the sex ratio of mature mites were recorded daily. The adult pre-oviposition period (APOP) (the period from adult emergence to first oviposition) and total preoviposition period (TPOP) (the period from egg to first oviposition) were also recorded.

Data analysis

The age-stage, two-sex life table approach was employed for analyzing the raw life-history data for *A. swirskii* (Chi & Liu, 1985; Chi, 1988). The computer program TWOSEX-MSChart (Chi, 2022) was used for estimating the life table parameters. The life history parameters, including the age-stage specific survival rate (s_{xj}) (where x = age, j = stage), age-stage specific fecundity (f_{xj}), the age-specific survival rate (l_x), age-specific fecundity (m_x), and the life table parameters (*GRR*, gross reproductive rate; R_0, net reproductive rate; r_m, intrinsic rate of increase; λ, finite rate of increase; and *T*, the mean generation) were calculated.

The net reproductive rate (R_0), as the mean number of offspring an individual can produce during its lifetime, was calculated as:

$$R_0 = \sum_{x=0}^{\infty} l_x m_x$$

The intrinsic rate of increase was estimated using the iterative bisection method from the Euler–Lotka formula with age indexed from 0 (Goodman, 1982):

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

The mean generation time was computed as $T = (\ln R_0)/r_m$. The gross reproductive rate (GRR) was calculated as $\sum m_x$. The age-stage life expectancy (e_{xj}) was calculated according to Chi & Su (2006). The reproductive value (v_{xj}) is considered as the expectation of future offspring of individuals of age x and stage j (Fisher, 1930). The variances and standard errors of population parameters of *A. swirskii* were calculated using bootstrap techniques (Efron & Tibshirani, 1993; Huang & Chi, 2012) with 100,000 resamplings, according to confidence interval based on paired bootstrap differences (Wei *et al.*, 2020). Sigma plot 12.5 was used to create graphs.

Functional response

Since the life history experiment showed that the egg stage of *B. tabaci* is more suitable than other immature stages of *B. tabaci* for the development and reproduction of *A. swirskii*, this experiment was conducted only on eggs of *B. tabaci*. Therefore, to study the functional response of *A. swirskii* feeding on different densities of *B. tabaci* eggs, a square piece of cucumber leaf (4 cm length) was placed on a layer of agar in a Petri dish mentioned above. We followed the densities of *B. tabaci* eggs used by Barbosa *et al.* (2019). Different densities of 5, 10, 20, 30, 45, and 60 *B. tabaci* eggs were presented separately to a mated *A. swirskii* female mite (less than 24-h old) on the cucumber leaf. Experiments were replicated 10 times simultaneously for each treatment. After 24 hours, mites were removed from the experimental unit, and the number of eggs eaten by each female *A. swirskii* was recorded.

The two-step method of Juliano (2001) was used in the statistical program SAS 9.2 (SAS Institute, 2012) to analyze the data. First, to determine the type of functional response, logistic regression of the proportion of eaten prey (N_a) concerning initial prey density (N_0) was calculated using the following polynomial logistic function:

$$1)\quad \frac{N_a}{N_0} = \frac{P_0 + P_1 N_0 + P_2 N_0^2 + P_3 N_0^3}{1 + \exp(P_0 + P_1 N_0 + P_2 N_0^2 + P_3 N_0^3)}$$

where P_0, P_1, P_2 and P_3 are the constant, linear, quadratic, and cubic parameters to be calculated (CATMOD procedure). Significant negative or positive linear regression coefficients (i.e., P_1) denote type II or type III responses, respectively (Juliano, 2001). In the second step, a non-linear least square regression (NLIN procedure) was applied to estimate handling time (T_h) and searching efficiency or attack rate (a'), using Rogers's random predator equation (Rogers, 1972).

$$2)\quad N_a = N_0\{1 - \exp[a(T_h N_a - T)]\}$$

Where T is the total time available for the predator, a' is the attack rate, and T_h is the handling time in hours.

Numerical response

This test was performed in the same experimental conditions as the functional response test. Different densities of *B. tabaci* eggs (5, 10, 20, 30, and 45) were offered to a mated *A. swirskii* female (less than 24-h-old) on cucumber leaves placed on a layer of agar in a Petri dish. After 24 hours, the mites were removed from the experimental unit and placed on a new experimental unit containing cucumber leaves with similar densities of *B. tabaci* eggs. Then, the number of eggs laid by *A. swirskii* in the earlier experimental unit was counted. This procedure was repeated every day until the death of the female mite. This experiment was performed in 10 replicates for each prey density in the form of a complete randomized design. A regression line was fitted to numerical response data as well (Amiri-Jami and Sadeghi-Namaghi, 2014).

Results

Preadult development, survivorship and sex ratio

Amblyseius swirskii could successfully complete its development only when fed on egg and first nymphal stage of *B. tabaci*. The predatory mite died during the larval or first nymphal stage when offered the second, third, or fourth nymphal stages of *B. tabaci*. The duration of different developmental stages of *A. swirskii* by feeding on the eggs and first-instar nymphs of *B. tabaci* is shown in Table 1. In females, the total pre-adult period of *A. swriskii* was significantly shorter on 1st instar nymphs of *B. tabaci* (5.12 d.) than on eggs of *B. tabaci* (5.62 d). In males, the total pre-adult period of *A. swirskii* was significantly shorter on eggs of *B. tabaci* (5.28 d.) than on 1st instar nymphs of *B. tabaci* (5.70 d) (Table 1).

The survival rate of *A. swirskii* fed on egg and the first nymphal stage of *B. tabaci* was recorded as 100% for both diets. Age-stage-specific survival rate (s_{xj}) represents the probability that a newborn egg would survive to age x and stage j (Fig. 1). Overlaps between different stages explain the variable developmental rates among individuals. The probability that a newborn mite would survive to the adult stage in 8 days increased from 0.32 to 0.37 for males and 0.33 to 0.37 for females by feeding on 1st instar nymphs and eggs, respectively. The daily mean number of offspring produced by individual *A. swirskii* of age x and stage j per day is indicated with the age-stage fecundity (f_{xj}) in Fig. 2. l_x is the age-specific survival rate as an overview of the survival history of the whole cohort (Fig. 2). Age-specific fecundity (m_x), age specific-maternity ($l_x m_x$) and age-stage specific fecundity (f_{xj}) curves showed the highest peaks by feeding on eggs of *B. tabaci* (Fig. 2).

Adult longevity, fecundity and sex ratio

The highest adult pre-oviposition period of *A. swirskii* was recorded on 1st instar nymphs of *B. tabaci*. However, there was no significant difference between the two offered diets in the total pre-oviposition period and mean oviposition period between two tested diets. Adult longevity also showed no significant difference. Based on the present result, fecundity was significantly reduced by feeding on 1st instar nymphs of *B. tabaci* (Table 2). The sex ratio (female percentage) of *A. swirskii* feeding on eggs and 1st instar nymphs of *B. tabaci* was calculated as 70±0.01 and 72±0.02%, respectively, with no significant differences (t test: p> 0.05).

Life table parameters

The population growth parameters of *A. swirskii* are presented in Table 3. The intrinsic rate of increase (r_m) increased by feeding on eggs (0.2040 days^{-1}) compared to 1st instar nymphs (0.1863 days^{-1}) of *B. tabaci* with no significant difference. Other parameters such as finite rate of increase (λ), net reproductive rates (R_0), gross reproductive rate (GRR), mean generation time (T), and doubling time (DT) showed no significant difference between the two offered diets. The age-stage-specific life expectancy (e_{xj}) is the time that an individual of age x and stage j is expected to survive starting at age x. The age-stage specific life expectancies (e_{xj}) of *A. swirskii* for two offered diets are shown in Fig. 3. As an example, the life expectancy of a newborn egg was about 23 and 21 d by feeding on eggs and 1st instar nymphs, respectively, while a female of age 6 d is expected to live 24 more days by feeding on eggs.

Table 1. Mean (±SE) duration of different preadult developmental stages of the mite *Amblyseius swriskii* male and female fed on eggs and 1st instar nymphs of *Bemisia tabaci* (*B. t*). Eggs and 1st instar nymphs were compared separately as prey in males and females

	Female of *A. swriskii*		Male of *A. swriskii*	
	Eggs of *B. t.*	1st instar nymphs of *B. t.*	Eggs of *B. t.*	1st instar nymphs of *B. t.*
Egg	0.93 ± 0.08[a]	1.13 ± 0.10[a]	1.10 ± 0.81[a]	1.13 ± 0.09[a]
Larva	1.38 ± 0.06[a]	1.25 ± 0.08[a]	1.73 ± 0.07[a]	1.52 ± 0.07[b]
Protonymph	1.62 ± 0.07[a]	1.45 ± 0.08[a]	1.73 ± 0.07[a]	1.55 ± 0.09[a]
Deutonymph	1.68 ± 0.07[a]	1.28 ± 0.07[b]	1.72 ± 0.07[a]	1.50 ± 0.09[a]
Total preadult	5.62 ± 0.13[a]	5.12 ± 0.17[b]	5.28 ± 0.19[b]	5.70 ± 0.20[a]

Values in rows followed by the same letter are not significantly different, using the confidence interval based on paired bootstrap differences at 5% significance level (Males and females of *A. swirskii* compared separately).
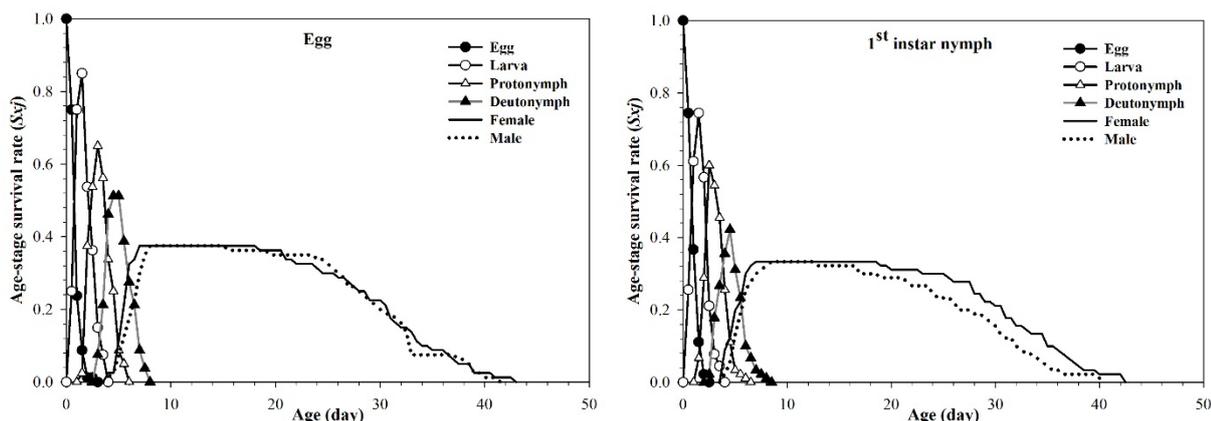
Fig. 1. Age-stage survival rate (S_{xj}) of *Amblyseius swriskii* on eggs and 1st instar nymphs of *Bemisia tabaci*

The age stage reproductive value (v_{xj}) of *A. swriskii* depicts the contribution of an individual of age *x* and stage *j* to the future population at different treatments (Fig. 4). The reproductive value of a newborn (v_{01}) is the finite rate itself. The maximum reproductive peak of females reared on eggs of *B. tabaci* occurred on 8th day (v_8=11.21), and for those reared on 1st instar nymphs were recorded on 7th day (v_7=10.31).

Functional response

The mean number of eggs consumed by *A. swirskii* varied based on prey densities (Table 4). The analysis of variance revealed a significant difference in prey densities in the number of eggs consumed by *A. swirskii* (F=120.67; df= 5, 348; $P < 0.0001$). The highest average number of eggs consumed by a female *A. swirskii* during 24 hours was 38.50 eggs, which was recorded at a density of 60 eggs of *B. tabaci* (Table 4).

The functional response of *A. swirskii* was type II on eggs of *B. tabaci* (Fig. 5). The linear coefficient of function (1) was negative and significantly different from 0 ($P<0.005$), indicating that the proportion of eaten prey decreases as prey density increases (Table 5). Rogers's random predator equation was used to estimate the functional response parameters (Table 6). The attack rate (a) and handling time (T_h) of *A. swirskii* were 0.1056 h^{-1} and 0.3534 h, respectively. The maximum attack rate (T/T_h) was 67.91 eggs/day.

Numerical response

Our results showed that with the increase in prey density, the average number of eggs of the female *A. swirskii* mite increased from 28 ± 2.08 eggs in the density of 5 to 36 ± 2.53 eggs in the density of 45 *B. tabaci* eggs, with no significant difference (F=1.96; df=4, 45; $P>0.05$) (Fig. 6).
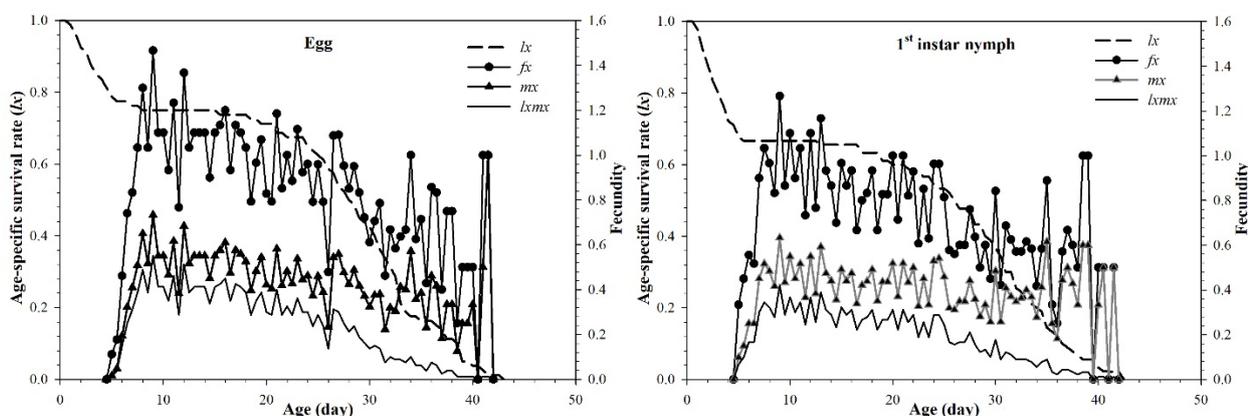
Fig. 2. Age-specific survival rate (*lx*), female age-specific fecundity (*fx*), age-specific fecundity (*mx*), and maternity (*lxmx*) of *Amblyseius swriskii* on eggs, and 1st instar nymphs of *Bemisia tabaci*.

Table 2. Mean (±SE) adult preoviposition period (APOP), total preoviposition period (TPOP), oviposition period, adult longevity, fecundity and sex ratio of *Amblyseius swirskii* fed on eggs and 1ˢᵗ instar nymphs of *Bemisia tabaci*

	Eggs of *B. tabaci*	1ˢᵗ instar nymphs of *B. tabaci*
APOP (days)	1.00 ± 0.13[b]	1.42 ± 0.11[a]
TPOP (days)	6.62 ± 0.17[a]	6.53 ± 0.19[a]
Oviposition days	16.97 ± 0.67[a]	16.47 ± 0.66[a]
Female longevity (days)	25.27 ± 1.09[a]	26.97 ± 1.06[a]
Male longevity (days)	24.40 ± 1.13[a]	22.08 ± 1.16[a]
Fecundity (eggs/female)	47.20 ± 1.94[a]	41.70 ± 1.79[b]
Sex ratio (%)	70.00±0.01[a]	72.00±0.02[a]

Values in rows followed by the same letter are not significantly different, using the confidence interval based on paired bootstrap differences at 5% significance level (t test used for sex ratio).

Discussion

In the current study, the mean preadult developmental duration of *A. swirskii* female fed on egg and first nymphal stage of *B. tabaci* was recorded as 5.62 and 5.12 days at 25 °C, respectively. In an experiment with *A. swirskii* fed on different immature stages of *B. tabaci*, Nomikou *et al.* (2001) found the mean preadult duration to be 5.1 and 6.0 days at 25 °C for Bet-Dagan and Revadim strains, respectively, which is close to the results of the present study. Seiedy *et al.* (2017) also reported the mean preadult developmental duration of *A. swirskii* female fed on eggs of *B. tabaci* to be 6.0 days at 25 °C, which is similar to our results. However, Momen *et al.* (2013) reported the mean developmental duration of *A. swirskii* female fed on egg stage of *B. tabaci* to be 5.0 days at 28 °C, which is shorter than our results. This difference may be explained by the disparity in temperatures used during the two experiments.

The mean preadult survival of *A. swirskii* fed on both egg and first instar nymphal stages of *B. tabaci* was 100%. Nomikou *et al.* (2001) reported the mean preadult survival rate of *A. swirskii* fed on different immature stages of *B. tabaci* to be 100 and 93 % for Bet-Dagan and Revadim strains, respectively, which is similar to the results of the present study.

In the current study, the mean sex ratio (female percentage) of *A. swirskii* fed on egg and first instar nymphal stages of *B. tabaci* was 70 and 72 %, respectively. Nomikou *et al.* (2001) reported the mean sex ratio (female percentage) of two strains of Bet-Dagan and Revadim of *A. swirskii* fed on different growth stages of *B. tabaci* as 74 and 64%, respectively, which is similar to our results. In the present study, the mean longevity of *A. swirskii* female fed on eggs and first instar nymphs of *B. tabaci* was 25.27 and 26.97 days, respectively. Seiedy *et al.* (2017), in a similar study, reported the longevity of female *A. swirskii* fed on *B. tabaci* eggs as 25.35 days, which corresponds well with our results. The results of our study showed that the longevity of male *A. swirskii* was shorter than that of female mites. A similar trend has been reported for *A. swirskii* mite feeding on bee pollen (Goleva & Zebitz, 2013) and *T. urticae* (Riahi *et al.*, 2017). In the current study, the mean number of daily eggs of *A. swirskii* fed on eggs and the first nymphal stage of *B. tabaci* was 1.89 and 1.55 eggs, respectively. The mean number of daily eggs of *A. swirskii* fed on *B. tabaci* eggs was reported to be 1.0 and 1.66 eggs (for Bet-Dagan and Revadim strains) (Nomikou *et al.*, 2001), 1.2 eggs (Fouly *et al.*, 2011) and 1.8 eggs (Calvacante *et al.*, 2015), which is close to our results.

Table 3. The mean (± SE) population parameters of *Amblyseius swirskii* reared on eggs and 1ˢᵗ instar nymphs of *Bemisia tabaci*

	Eggs of *B. tabaci*	1ˢᵗ instar nymphs of *B. tabaci*
Intrinsic rate of increase (r_m) (d⁻¹)	0.2040 ± 0.0137[a]	0.1863 ± 0.0142[a]
Finite rate of increase (λ) (d⁻¹)	1.2264 ± 0.0167[a]	1.2048 ± 0.0171[a]
Net reproductive rate (R_0) (offspring)	17.7000 ± 2.6685[a]	13.9000 ± 2.151[a]
Gross reproductive rate (offspring)	31.9328 ± 4.6708[a]	29.6445 ± 3.8623[a]
Mean generation time (T) (d)	14.0827 ± 0.3749[a]	14.1282 ± 0.4072[a]
Doubling time (DT) (d)	3.3970 ± 0.2397[a]	3.7209 ± 0.3007[a]

Values in rows followed by the same letter are not significantly different, using the confidence interval based on paired bootstrap differences at 5% significance level.
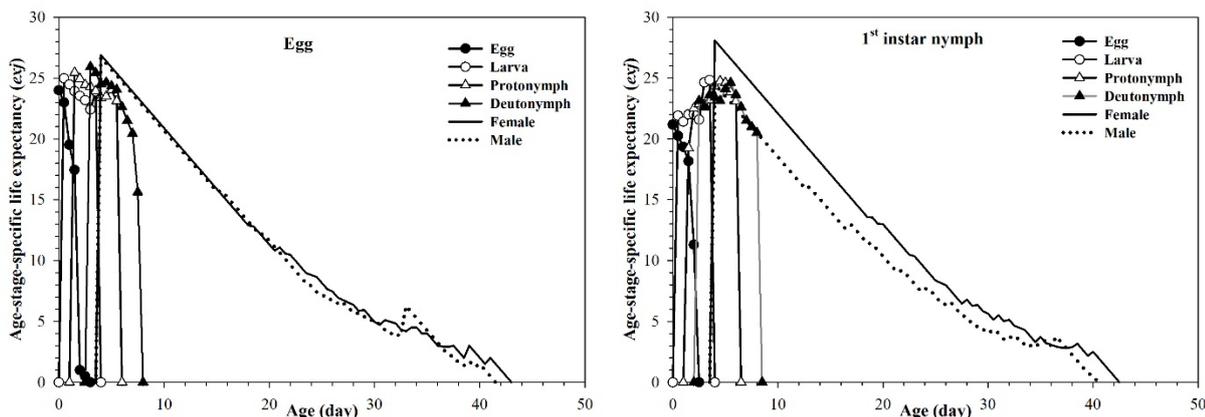
Fig.3. Age-stage-specific life expectancy (*exj*) of *Amblyseius swriskii* on eggs and 1ˢᵗ instar nymphs of *Bemisia tabaci*
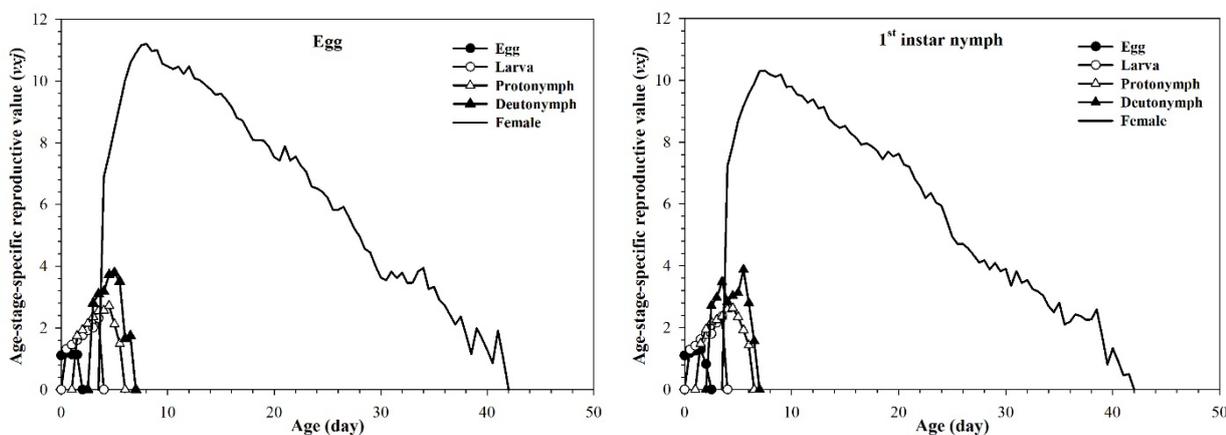
Fig.4. Age- stage-specific reproductive value (*vxj*) of *Amblyseius swriskii* on eggs and 1ˢᵗ instar nymphs of *Bemisia tabaci*

In the current study, the mean number of total eggs of *A. swirskii* feeding on eggs and first instar nymphs of *B. tabaci* were 47.20 and 41.70, respectively. Seiedy *et al.* (2017), in a similar study, reported the mean total number of eggs of female *A. swirskii* feeding on *B. tabaci* eggs as 19.22 eggs, which is lower than our findings. The differences may be explained by strain differences of *A. swirskii* and *B. tabaci*. Gerson *et al.* (2003) reported that different strains of phytoseiid species exhibit different biological characteristics. We purchased the *A. swirskii* strain from Abadagrico, Hamedan, while Seiedy *et al.* (2017) obtained *A. swirskii* strain from Koppert Biological Systems Inc., Netherlands. The intrinsic rate of population increase is one of the important parameters in determining the type and rate of population growth, which in turn indicates the increase in population stability or decline (Birch, 1948).

Table 4. Mean (± SE) of daily prey eaten by the female predatory mite *Amblyseius swriskii* at different densities of *Bemisia tabaci* eggs

Prey density	Prey consumption by the female predator	Range
5	4.70 ± 0.21ᵉ	3-5
10	8.70 ± 0.66ᵈ	4-10
20	16.30 ± 1.21ᶜ	10-20
30	23.40 ± 1.55ᵇ	16-30
45	34.70 ± 1.54ᵃ	25-42
60	38.50 ± 2.39ᵃ	25-48

Means followed by different letters are significantly different (*P*<0.05, Tukey's test).

Table 5. Results on logistic regression of proportion of the *Bemisia tabaci* eggs consumed by the female of *Amblyseius swriskii* against initial number of offered eggs

Coefficient	Estimate	SE	χ^2	*P* value
Intercept	3.3144	0.6291	27.7531	<0.0001
Linear	-0.1794	0.0638	7.9047	0.0049
Quadratic	0.00512	0.00193	7.0603	0.0079
Cubic	-0.00005	0.000017	7.5937	0.0059

In the present research, the value of this parameter for the predatory mite *A. swirskii* fed on eggs and first instar nymphs of *B. tabaci* was calculated as 0.204 and 0.186 per day, respectively. In a similar study, Seiedy *et al.* (2017) reported the r_m value of 0.120 for *A. swirskii* fed on cotton whitefly eggs, which is lower than our results. The difference in the strain of the predatory mite or difference in the strain of the whitefly may be the reason for the difference in the results.

At 25 °C the r_m value of *B. tabaci* was reported to be 0.131 day^{-1} on cucumber (Tsai & Wang, 1996), 0.092, 0.141, and 0.165 day^{-1} on tomato, eggplant, and potato, respectively (Fekrat, 2002) and 0.136 day^{-1} on cucumber (Zandi Sohani *et al.*, 2007). Our results showed that the r_m value of *A. swirskii* fed on eggs and first nymphal stages of *B. tabaci* was 0.204 and 0.186 day^{-1}, respectively, higher than that of *B. tabaci*. Therefore, we conclude that the predatory mite *A. swirskii* has a good potential to control *B. tabaci* population.

The length of a generation (*T*) is one of the important criteria in the life table parameters, which directly impacts the population growth rate (Croft, 1990). In the current study, the average duration of one generation (*T*) of *A. swirskii* fed on eggs and first-instar nymphs of *B. tabaci* was estimated as 14.08 and 14.12 days, respectively. In a similar study, Seiedy *et al.* (2017) reported the duration of one generation of *A. swirskii* feeding on *B. tabaci* eggs as 11.24 days, which is lower than our results. Again, the differences between the strains of prey and predator may explain the differences in generation times.

A. swirskii showed type II functional response to the different densities of *B. tabaci* eggs. Similarly, Fathipour *et al.* (2017) reported type II functional response for 3, 4, 5, 6, and 7-day-old adult female *A. swirskii* fed on different densities of *T. urticae*. In the second type of functional response, the number of prey eaten per predator first increases with increasing prey density, then gradually decreases, and finally, the respective curve extends parallel to the horizontal axis. The review of the literature showed that so far, only two studies have been conducted on the functional response of a phytoseiid mite by feeding on different densities of *B. tabaci* eggs. In a similar study, Nawar & Imam (2019) studied the functional response of *A. swirskii* on different densities (2, 4, 8, 10, 12, 14) of the immature stage of *B. tabaci* reared on bean (*Phaseolus vulgaris* L.) leaves.

The result of our research (type II functional response) is similar to their findings. However, in the current study, the attack rate (*a*) of *A swirskii* fed on different densities of *B. tabaci* eggs was estimated to be 0.1056, higher than 0.0298 reported by Nawar & Imam (2019). In addition, the handling time (*Th*) of female *A. swirskii* feeding on different densities of eggs of *B. tabaci* in our study (0.3534 h) was shorter than the value of handling time (0.492 h) of *A. swirskii* fed on different densities of immature stages of *B. tabaci* found by Nawar & Imam (2019). These differences may be attributed to the disparities in experimental conditions such as strains of *A. swirskii* and *B. tabaci*, host plant species of whitefly, and different densities of prey used in the two studies. Nawar & Imam (2019) used a native species of *A. swirskii* while we purchased it from Abadagrico, Hamedan, Iran. In addition, they used bean leaves as the host of *B. tabaci*, while we used cucumber leaves.

Table 6. Estimated functional response parameters by the Rogers' equation for female mite predator *Amblyseius swriskii* to densities of the *Bemisia tabaci* eggs

Parameters	Estimate	Asymptotic SE	Asymptotic 95% CI		(*T/Th*)	r^2
			Lower	Upper		
					67.91	0.89
(*a*)	0.1056	0.0224	0.0608	0.1505		
(*Th*)	0.3534	0.0703	0.2127	0.4941		
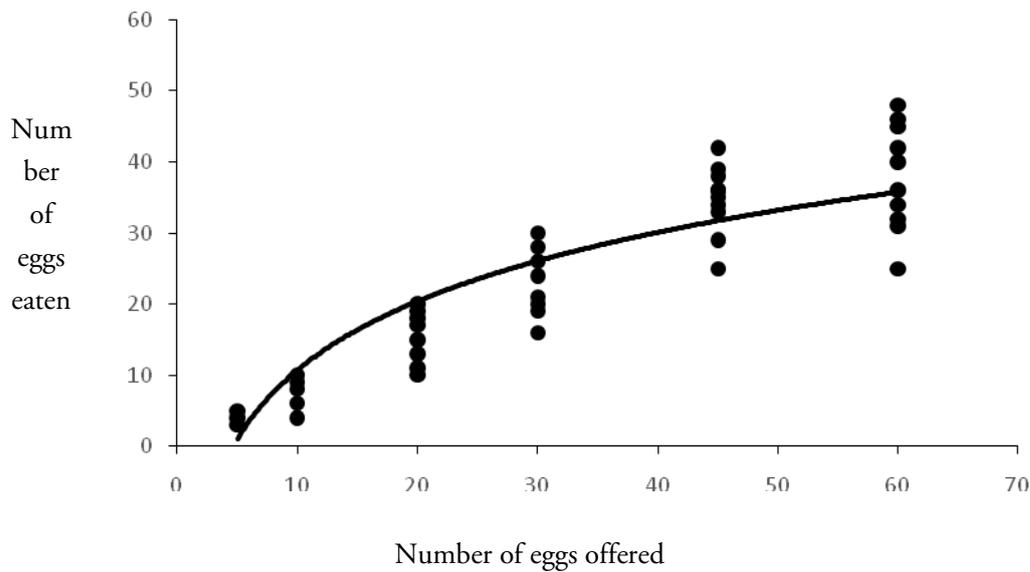
Fig.5. Functional response of female mite predator *Amblyseius swriskii* by feeding on varying densities of the *Bemisia tabaci* eggs.

Furthermore, they used different densities (2, 4, 8, 10, 12, and 14 immature stages) of *B.tabaci* while we used other densities (5, 10, 20, 30, 45, and 60 eggs) of *B. tabaci*. Barbosa *et al.* (2019) also investigated the functional response of the phytoseiid mite *Amblyseius tamatavensis* Blommers on different densities of *B. tabaci* eggs grown on different host plants. The mean number of eggs fed by *A. tamatavensis* in the highest density (45 eggs of *B. tabaci*) grown on tomato, bean, potato, melon, and cotton was 6.9, 8.2, 8.7, 7.1, and 9.2, respectively. Comparing our results with the results of Barbosa *et al.* (2019) shows that the *A. swirskii* mite consumed more eggs (34.7) at the same density in our study. Barbosa *et al.* (2019) also reported a type II functional response for *A. tamatavensis* fed on different densities of *B. tabaci* eggs grown on different host plants. The literature review showed that no study had been conducted on the numerical response of *A. swirskii* fed on different prey. Other laboratory studies with a sufficient amount of prey have reported a variety of fecundity values for this species. At 25 °C, the fecundity of *A. swirskii* was reported to be 17.9 eggs on *Eutetranychus orientalis* (Klein) (Metwally *et al.*, 1984), 38.1 eggs on *Aculops lycopersici* (Massee) (Park *et al.*, 2010), 54.90 eggs on *Panonychus citri* (McGregor) (Ji *et al.*, 2013), 40.85 eggs on *Tetranychus urticae* Koch (Riahi *et al.*, 2017), 34.69 eggs on *Eotetranychus frosti* (McGregor) (Bazgir *et al.*, 2018), 82.17 eggs on *Carpoglyphus lactis* (L.) (Asgari *et al.*, 2020), and 45.52 eggs on *T. turkestani* (Rahmani Piyani *et al.*, 2021).
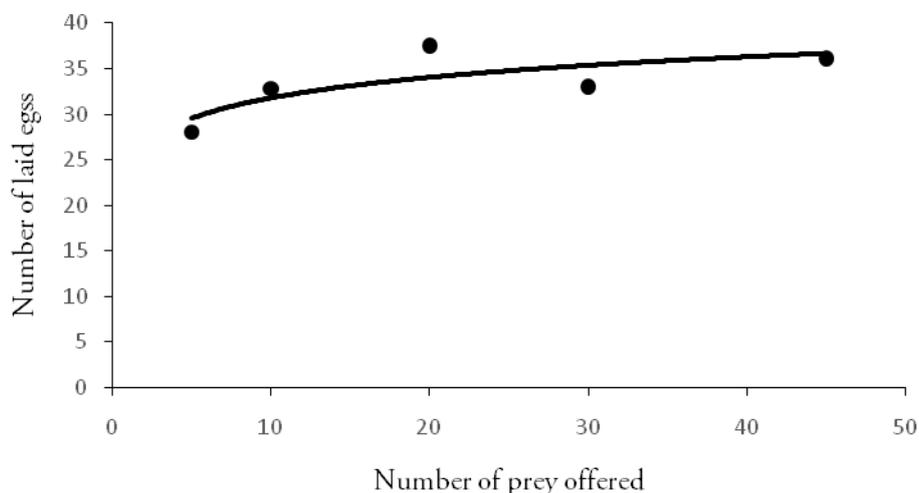
Fig.6. Number of eggs laid by female mite predator *Amblyseius swriskii* at different densities of prey. Points and line represent the mean of observed values and predicted values, respectively.

The findings of the current study have enriched our knowledge of the *A. swirskii- B. tabaci* interaction in the laboratory condition and could be used for the development of a better strategy for the biological control of *B. tabaci* by this predator. The present results suggest that *A. swirskii* could be considered for augmentative biological control of *B. tabaci* on cucumber in the glasshouse or field conditions. However, it is reasonable to recommend conducting additional studies in a more natural environment.

Acknowledgments

Funding

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ویژگی‌های زیستی، واکنش تابعی و عددی کنه شکارگر(Acari: Phytoseeidae) *Amblyseius swirskii* با تغذیه از سفیدبالک پنبه(Hemiptera: Aleyrodidae) *Bemisia tabaci*

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چکیده

کنه *Amblyseius swirskii* Athias-Henriot توجهات اساسی را به عنوان یک عامل کنترل بیولوژیک به خود جلب کرده است. تاریخچه زندگی و واکنش تابعی و عددی *A. swirskii* با تغذیه از (Gennadius) *Bemisia tabaci* در شرایط آزمایشگاهی (۲۵±۲ درجه سلسیوس، ۶۰±۵٪ رطوبت نسبی، ۱۶ ساعت روشنایی: ۸ ساعت تاریکی) مطالعه شد. دوره رشدی مراحل نابالغ، بقا و زادآوری *A. swirskii* بوسیله قراردادن تخم‌های تازه کنه روی برش‌های گرد از برگ خیار (به قطر ۲/۵ سانتی‌متر) و آلوده به مراحل مختلف نابالغ *B. tabaci* ارزیابی شد. نتایج نشان داد که کنه شکارگر قادر به تغذیه و تکمیل رشدش روی تخم و پوره‌های سن یک *B. tabaci* بود. کل دوره رشدی قبل از بلوغ ماده *A. swirskii* با تغذیه از تخم و پوره‌های سن یک *B. tabaci* به ترتیب ۵/۶۲ و ۵/۱۲ روز بود. نسبت جنسی (درصد ماده) *A. swirskii* با تغذیه از رژیم‌های غذایی مذکور به ترتیب ۷۰ و ۷۲٪ بود. با تغذیه از رژیم‌های غذایی مذکور، طول عمر ماده بالغ *A. swirskii* به ترتیب ۲۵/۲۷ و ۲۶/۹۷ روز و زادآوری کل ۴۷/۲۰ و ۴۱/۷۰ تخم بود. نرخ ذاتی افزایش جمعیت (r_m) در *A. swirskii* با تغذیه از رژیم‌های غذایی مذکور به ترتیب ۰/۲۰۴۰ و ۰/۱۸۶۳ بر روز بود. با استفاده از رگرسیون لجستیک، واکنش تابعی کنه *A. swirski* با تغذیه از تراکم‌های مختلف (۵، ۱۰، ۲۰، ۳۰، ۴۵ و ۶۰) تخم *B. tabaci* از نوع دوم تعیین شد. بیشترین میانگین تعداد طعمه مصرف شده بوسیله یک عدد کنه ماده *A. swirski* در تراکم‌های ۶۰ و ۴۵ طعمه به ترتیب ۳۸/۵۰ و ۳۴/۷۰ تخم و بدون تفاوت معنی‌دار ثبت شد. قدرت جستجو (a) و زمان دستیابی (T_h) کنه‌های ماده بر اساس رگرسیون غیرخطی حداقل مربعات، ۰/۱۰۵۶ بر ساعت و ۰/۳۵۳۴ ساعت تخمین زده شد. بیشترین نرخ شکارگری (T/T_h) کنه‌های ماده ۶۷/۹۱ تخم در روز بود. با افزایش تراکم طعمه، واکنش عددی (تعداد تخم‌های گذاشته شده) کنه معنی‌دار نبود. در مجموع، نتایج مطالعه حاضر نشان داد که کنه *A. swirski* پتانسیل خوبی برای کنترل *B. tabaci* دارد. بنابراین پژوهش‌های بیشتری در این زمینه در گلخانه و مزرعه مورد نیاز است.

کلمات کلیدی: نرخ حمله، زادآوری، زمان دستیابی، جدول زندگی، تراکم طعمه