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Functional response of abamectin and bifenazate resistant and native populations of *Amblyseius swirskii* Athias-Henriot (Acari: Phytoseiidae)

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Original research


ABSTRACT

This study aimed to investigate the impact of acaricides on the predatory capacities of native (NP) and acaricide-resistant (RP) populations of *Amblyseius swirskii* Athias-Henriot (Acari: Phytoseiidae). The RP was obtained in a previous study through six successive selections of abamectin and bifenazate from the NP of *A. swirskii*, resulting in a 25-fold resistance level. The functional and numerical responses of the NP and RP populations were evaluated under untreated conditions (control) and after treatment with the recommended concentration (100 ml/100 L distilled water) of an abamectin+bifenazate mixture at 27 ± 1 °C, under a 16:8 (L:D) photoperiod and $80 \pm 5\%$ relative humidity. The functional and numerical responses, as well as the related parameters of NP and RP females, were analyzed in response to different egg densities of *Tetranychus urticae* Koch (Tetranychidae). Logistic regression analysis indicated that the untreated RP and NP and the treated RP exhibited a Type II functional response, whereas the treated NP exhibited a Type III functional response. The handling times for *T. urticae* eggs were recorded as 0.0454 and 0.0376 hours for the untreated NP and RP, respectively, while they were calculated as 0.0420 and 0.0381 hours for the treated NP and RP, respectively. The handling time (Th) increased significantly in NP after acaricide treatment. The Th value of RP was not affected by acaricide treatment. The attack rate coefficients (α) varied considerably among the populations and treatments, with the highest value observed in the untreated RP (1.27), followed by the treated RP (1.13), the untreated NP (1.00), and the treated NP (0.71). Under untreated conditions, *A. swirskii* exhibited a higher α value in the RP population than the NP population. Our findings indicate that the resistant *A. swirskii* population can effectively feed on *T. urticae* eggs and oviposit, even at low prey densities and under acaricide-treated conditions.

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Introduction

Predatory mites are key biocontrol agents of various phytophagous mites and some other agricultural pests, playing a crucial role in suppressing their populations (Helle and Sabelis 1985; McMurtry and Croft 1997). Among target preys, spider mites (Acari: Tetranychidae) are highly destructive and widely distributed pests affecting numerous crops and ornamental plants. The development of resistance to acaricides in these pests has necessitated extensive research into alternative control methods. Recent studies on the biological control of tetranychid mites have primarily focused on the Phytoseiidae family due to their efficacy in maintaining

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prey populations at low densities (Song *et al.* 2016; Park *et al.* 2021). The predatory mite *Amblyseius swirskii* Athias-Henriot (Acari: Phytoseiidae) is a highly effective biocontrol agent widely used for managing whiteflies, thrips, and spider mites in both open-field and greenhouse crops (McMurtry *et al.* 2013; Calvo *et al.* 2015; Knapp *et al.* 2018). Its relatively low-cost mass production has contributed to its widespread adoption as a biocontrol agent. Beyond its ability to prey on a diverse range of pests, *A. swirskii* is a highly adaptable Type III generalist predator that can utilize non-prey resources such as pollen, allowing it to survive during periods of prey scarcity (McMurtry *et al.* 2013). Commercial populations of *A. swirskii* have been successfully integrated into integrated pest management (IPM) programs for controlling these pests (Calvo *et al.* 2012; Demirtaş *et al.* 2022; Kolcu and Kumral 2023).

Despite the significant potential of *A. swirskii* in controlling spider mites, whiteflies, and thrips, its predator-prey interactions remain insufficiently understood. While *A. swirskii* preys on spider mites, exclusive reliance on them may not be sufficient to keep their populations below the economic injury threshold in the long term (Mortazavi *et al.* 2019; Aly 2023). Although *A. swirskii* can prey on spider mites, its feeding preference is primarily directed towards whiteflies and thrips (Lopez 2023), which may reduce its effectiveness in suppressing *T. urticae* populations under certain conditions (Soleymani *et al.* 2016a,b; Yari *et al.* 2023). However, commonly used acaricides such as bifentazate and abamectin have been reported to exhibit high toxicity to *A. swirskii* when applied at recommended field concentrations (Fiedler and Sosnowska 2012; Döker and Kazak 2019; Kolcu and Kumral 2023). Bifenazate, a carbazate-based insecticide-acaricide, is among the most widely used pesticides worldwide for managing phytophagous mites. It primarily targets mitochondrial sites and exhibits non-systemic characteristics with contact and residual activity (van Nieuwenhuysse 2012; PPDB 2024). Abamectin, an avermectin-class insecticide-acaricide, is a natural fermentation product of *Streptomyces avermitilis* and exhibits high acute toxicity against numerous arthropod pests (PPDB 2024). Due to their mode of action, these pesticides do not exhibit specificity toward phytoseiids. Therefore, using an *A. swirskii* population resistant to these two acaricides could be a rational approach in IPM programs. In addition to the acute toxic effects of the recommended application doses, understanding their sublethal effects is crucial for assessing the predator's effectiveness (Havasi *et al.* 2021; Mousavi *et al.* 2022; Mousavi *et al.* 2023; Kolcu and Kumral 2023). Therefore, it is essential to thoroughly investigate the impact of these acaricides on the predatory mite's predator capacity.

Examining the functional response characteristics of natural enemies is a fundamental approach for assessing their efficiency in regulating pest populations (Fantinou *et al.* 2012). The type of functional response and its parameters can be influenced by various factors, including prey species, prey developmental stage, predator age, host plant characteristics, temperature, and humidity (Escudero and Ferragut 2005; Ahn *et al.* 2010; Farazmand *et al.* 2012; Döker *et al.* 2016; Song *et al.* 2016; Fathipour *et al.* 2017a,b). Recently, there has been increasing interest in understanding the functional response of *A. swirskii* to *Tetranychus urticae* Koch (Acari: Tetranychidae) (Xiao *et al.* 2013; Fathipour *et al.* 2017b; Fathipour *et al.* 2020). A previous study, showed that the life table parameters of resistant populations (RP) of *A. swirskii* were not significantly affected by the development of resistance (Doğan and Kumral 2025). Nevertheless, the effect of resistance on the functional response of this resistant strain remains unexplored. Additionally, previous functional response studies, which typically lasted only two days, may not fully capture the long-term effects of predation (Bazgir *et al.* 2020). Therefore, a distinctive aspect of the present study is the continuous assessment of predation capacity from the larval stage until adult mortality. A crucial step in evaluating the potential of *A. swirskii* to control *T. urticae* egg populations under both control and treatment conditions (NP and RP groups) is to analyze its functional response and consumption rate under varying prey densities. The aim of this study was to evaluate the potential impact of abamectin+bifenazate resistance on the functional and numerical responses of *A. swirskii* by comparing untreated individuals with those exposed to the recommended concentration of the acaricide. Specifically,



Figure 1 Map indicating the locations in Turkey where *Amblyseius swirskii* specimens were gathered.

the objectives were (i) to determine the functional response type and key parameters (attack rate and handling time), and (ii) to assess the effects on prey consumption and oviposition.

Materials and methods

Mite rearing

The native population (NP) of *A. swirskii* was initially collected in 2020 from an orange orchard located in the Kozan district of Adana province, Türkiye (Figure 1). This population was previously identified by Mertoğlu Boz *et al.* (2024) through both molecular and morphological identifications. The continuous mass rearing of this NP has been maintained under pesticide-free conditions in the Acarology and Toxicology Laboratory at Bursa Uludağ University. The abamectin- and bifenthrin-resistant population (RP) was developed from six successive selections of this NP in a prior study conducted by Doğan and Kumral (2025).

To sustain the nutrition of these populations, all developmental stages of *Carpoglyphus lactis* (L.) (Acari: Carpoglyphidae) and cattail pollen (*Typha latifolia* L.) were provided. Additionally, the green-form population of *Tetranychus urticae* Koch (Acari: Tetranychidae), which was used in all predatory capacity experiments, was maintained on the leaves of pepper plants (*Capsicum annuum* L., Burkalem cv., Bursa Tohum, Türkiye) under controlled conditions. All rearing procedures were conducted in regulated growth chambers set at 28 ± 1 °C, with a relative humidity of $80 \pm 5\%$, and a photoperiod of 16:8 h (light: dark cycle).

Chemicals

Saury, a commercially available acaricide (Sumi Agro, Türkiye), formulated with 125 g/L bifenthrin and 7.5 g/L abamectin as active ingredients, was utilized in biological assessments. This acaricide was specifically selected due to its approved registration for various vegetable crops. This, makes it a suitable option for the potential integration of *A. swirskii* in the biological control of mites, whiteflies, and thrips.

Acaricide treatments

The side effects of the recommended concentration (100 ml/100 L distilled water) of this acaricide formulation were previously evaluated for both the NP and RP of *A. swirskii* in our earlier study (Doğan and Kumral 2025). Based on acute toxicity results, the concentration was classified as moderately harmful (80–99%) for NP and harmless (<30%) for RP. According to the residual bioassay method, 2 mL of the recommended concentration was applied to the undersides of pepper leaves using a Potter Spray Tower (Burkard Scientific, Uxbridge, UK) (Overmeer and Van Zon 1982; Kumral *et al.* 2021). Briefly, the spraying process, conducted

for three seconds, resulted in a deposition of 1.5 mg of liquid per cm². The treated pepper leaves were then left to air-dry for 30 minutes at room temperature. As a control, leaves were sprayed with distilled water (Potter 1952). Plexiglas Munger cells (8 × 10 × 1 cm) with a central circular opening of 5 cm in diameter were used for the bioassay setup. The treated leaf, along with a filter paper, was placed between two Plexiglas plates—one featuring the circular opening and the other solid. The filter paper was lightly moistened with distilled water to maintain adequate moisture levels.

Functional and numerical response experiments

The treatments were administered at the suggested concentration under controlled environmental conditions, with a temperature of 28 ± 1 °C, a photoperiod of 16:8 hours (L:D), and a relative humidity of 80 ± 5%. Functional and numerical responses on both pesticide-treated and untreated (control) pepper leaves were evaluated through two-day experiments. The methodology for functional response assessment was adapted from Hull *et al.* (1977). Briefly, pesticide-treated or untreated (control) pepper leaves, as previously described, were placed in Munger cells and used as experimental arenas. To examine the functional and numerical responses of the predator in both populations (NP and R6), experiments were conducted using 15 *A. swirskii* females, aged 3–4 days, during their oviposition period. Before each experiment, the females were subjected to a 24-hour starvation period. On the following day, *T. urticae* eggs at varying densities (5, 10, 20, 40, and 80 eggs) were provided as prey, as this period was chosen to avoid any effects from the tested acaricides while ensuring a consistent prey supply (Chow *et al.*, 2010; Göksel and Kumral, 2022). Only eggs were selected as prey since the applied acaricides do not have ovicidal effects. The prey eggs were gently transferred onto leaf discs with a fine paintbrush (No. 0000). After 24 hours, the number of prey eggs consumed by each predator was recorded, and after 48 hours, the number of eggs laid was documented. No additional prey was provided during the second 24-hour period, and the predators remained undisturbed in the same experimental arenas throughout the 48-hour duration.

Prey consumption during development and adult life span

The prey consumption of *A. swirskii* populations, including both the native (NP) and resistant (RP) strains, was evaluated across their developmental stages and adult life span under both untreated (control) and acaricide-treated conditions. The acaricide treatment consisted of a formulation containing a combination of abamectin and bifenthrin, applied to bean leaves at the recommended field concentration. Biological observations were conducted using Munger cells, as previously described (Demard & Qureshi, 2023). Briefly, one newly emerged female and two males of *A. swirskii* were introduced into each Munger cell to allow for mating and oviposition. After 24 hours, all adults and surplus eggs were removed, ensuring that only a single egg remained on each leaf disc within the Munger cell. To provide a consistent prey supply, 50 *T. urticae* eggs were added weekly to each Munger cell as food for the predatory mites. Prey consumption was assessed by recording the number of *T. urticae* eggs consumed every 24 hours, starting from the larval stage and continuing until the death of both the male and female predatory mites. Each treatment was replicated 40 times. To maintain optimal environmental conditions, the phytoseiid mites were transferred from older leaves to freshly treated or untreated leaves at seven-day intervals. In the acaricide-treated groups, the leaves were sprayed immediately prior to transferring the mites.

Data analysis

The functional response data were analyzed in two stages, following the approach of Holling (1959). Initially, logistic regression was employed to assess the relationship between the proportion of prey consumed and the initial prey density, allowing for the identification of the

functional response curve shape for NP and RP of *A. swirskii* across different densities of *T. urticae* eggs.

$$N_e/N_0 = \frac{\exp(P_0 + P_1N_0 + P_2N_0^2 + P_3N_0^3)}{1 + \exp((P_0 + P_1N_0 + P_2N_0^2 + P_3N_0^3))} \quad (3.1)$$

In this context, N_e represents the number of prey consumed, N_0 denotes the initial prey density, and (N_e/N_0) indicates the probability of prey consumption. The parameters P_0 , P_1 , P_2 , and P_3 correspond to the intercept, as well as the linear, quadratic, and cubic coefficients, respectively, which were estimated using the maximum likelihood method. The type of functional response was determined based on the signs of P_1 and P_2 . If the linear coefficient was negative ($P_1 < 0$), the functional response was classified as Type II, as the proportion of prey consumed declined monotonically with increasing initial prey density (Jualino *et al.* 2001). In the next step, the handling time (Th) and attack rate (α) coefficients for a Type II functional response were analyzed using Rogers' random predator equation (Rogers 1972: Formula 3.2).

$$N_{ha} = N [1 - \exp \{-\alpha' (T - T_h N_{ha})\}] \quad (3.2)$$

If the functional response was classified as Type III, these parameters were calculated using the equation (Formula 3.3) proposed by Hassell *et al.* (1977).

$$N_{ha} = N (N - N_{ha}) \left[c \log \left\{ \frac{N - N_{ha}}{N} \right\} - bT_h N_{ha} + bT \right] \quad (3.3)$$

In the formulas, N represents the initial prey density, N_{ha} denotes the number of prey consumed by the predator, α' refers to the search rate, T indicates the duration of the trial within a specific trial area (days), T_h corresponds to the prey capture and feeding time (days), and b and c are the regression coefficients. Nonlinear regression was employed to estimate the attack rate and handling time parameters (Proc NLIN, SAS Institute). To evaluate the effects of prey density, population type (natural vs. resistant treated or untreated with the acaricide), and their interaction on prey consumption, we used a generalized linear model (GLM) with a binomial error distribution and a logit link function. The effects of acaricides on biological parameters of mites were statistically analyzed using one-way ANOVA with a significance level of $P < 0.01$ after checking for normality. Means were compared with the Tukey test accepting significant differences at $P < 0.01$. SPSS software version 23 was used for mean comparisons.

Results

Functional response

The results of the logistic regression analysis indicated a significantly negative linear coefficient ($P_1 < 0$) for all untreated NP populations, as well as for both treated and untreated RP populations, suggesting that the proportion of prey consumed decreased when prey density reached high levels. However, the treated NP population displayed a positive linear ($P_1 > 0$) and negative quadratic coefficient ($P_2 < 1$) across all prey intensities, indicating that individuals in this population were not present at low prey intensities. Consequently, while the untreated NP population, as well as the treated and untreated RP populations of *A. swirskii*, followed a Type II functional response across all prey intensities, the treated NP population exhibited a Type III functional response under the same conditions (Table 1).

The interaction between predator populations and prey density had a significant effect on the number of prey consumed (population $F = 16.49$, $P < 0.01$; prey consumption $F = 951.72$, $P < 0.01$; population x prey consumption $F = 951.72$, $P < 0.01$). At prey densities ranging from 5 to 40 eggs, the highest consumption was observed in the untreated RP population, whereas the lowest consumption rate was recorded in the treated NP population (Table 2, Figure 2 and 3). In these prey density ranges, the highest consumption occurred in the untreated RP population,

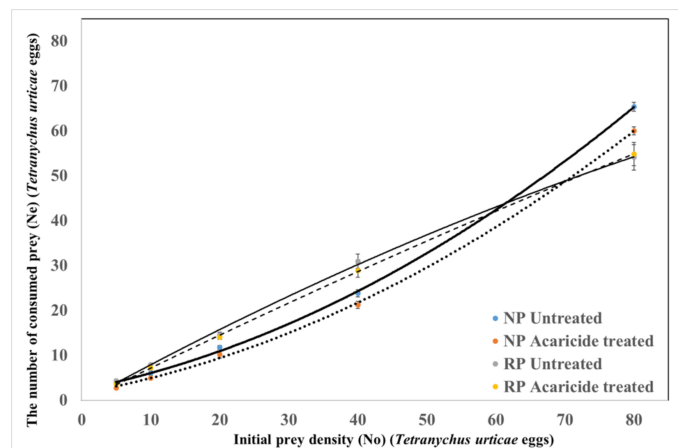


Figure 2 Functional response of adult females of *Amblyseius swirskii* feeding on *Tetranychus urticae* eggs. Points show an average number of individuals consumed or killed by the predator at each level of initial prey density. Error bars show standard errors.

followed by the RP population treated with the recommended concentration. These differences in prey consumption were statistically significant. At a prey density of 80 eggs, no significant differences were observed between the consumption rates of the treated NP population and those of the untreated and treated RP populations. The consumption rate of both treated and untreated RP populations, as well as the untreated NP population, gradually increased as prey density increased. However, in the treated NP population, prey consumption was either significantly lower or absent at low prey densities, suggesting a reduced ability to locate prey under these conditions. The untreated NP population consumed between 60% and 88% of *T. urticae* eggs, whereas the treated NP population consumed only 50% to 75% of the eggs across all prey densities (5, 10, 20, 40, and 80). The consumption rates of treated and untreated RP

Table 1 Maximum likelihood estimates and predation type classification results were obtained through logistic regression analysis to assess the functional response of *Amblyseius swirskii* adult females at varying prey (*Tetranychus urticae* egg) densities (No).

Populations/Treatments	Parameters	Estimate ± SE	χ^2	P-value	Functional response
NP Untreated ^a	Intercept (P ₀)	0.7176± 0.0962	7.46	<0.01	TYPE II (P ₁ < 0) and Probability value is significant
	Linear (P ₁)	-0.0133±0.0059	-2.25	0.026	
	Quadratic (P ₂)	-0.0003±0.0004	-0.65	0.519	
	Cubic (P ₃)	0.0000006±0.000001	0.71	0.476	
NP Acaricide treated ^b	Intercept (P ₀)	0.5985±0.1149	5.21	<0.01	TYPE III (P ₁ > 0) and (P ₂ < 0)
	Linear (P ₁)	0.00085±0.0064	0.13	0.895	
	Quadratic (P ₂)	-0.000596± 0.0005	-1.15	0.254	
	Cubic (P ₃)	0.0000006±0.000013	0.47	0.638	
RP Untreated ^c	Intercept (P ₀)	0.6073±0.07361	8.25	<0.01	TYPE II (P ₁ < 0) and Probability value is significant
	Linear (P ₁)	-0.0132±0.0039	-3.39	<0.01	
	Quadratic (P ₂)	0.00063±0.0004	1.82	0.71	
	Cubic (P ₃)	-0.000011± 0.0000007	-1.6	<0.01	
RP Acaricide treated ^d	Intercept (P ₀)	0.5600±0.0725	7.72	<0.01	TYPE II (P ₁ < 0) and Probability value is significant
	Linear (P ₁)	-0.0152±0.0037	-4.15	<0.01	
	Quadratic (P ₂)	0.001072±0.0003	3.32	0.07	
	Cubic (P ₃)	-0.000002± 0.0000007	1.05	0.11	

^a Acaricide-untreated natural population

^b Natural population treated with the recommended concentration of bifentazate and abamectin

^c Acaricide-untreated resistant population

^d Resistant population treated with the recommended concentration of bifentazate and abamectin

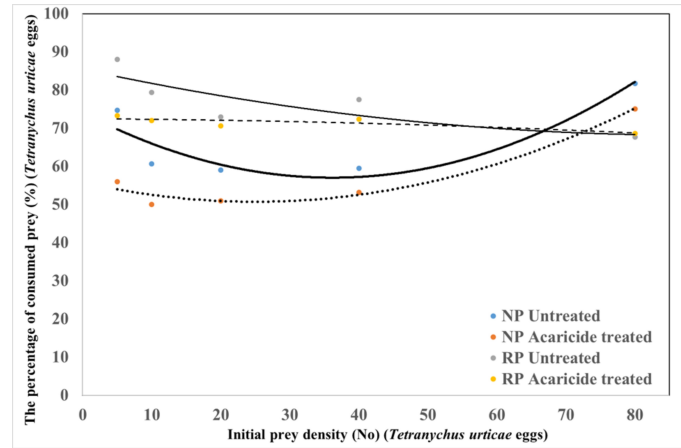


Figure 3 Functional response of adult females of *Amblyseius swirskii* feeding on *Tetranychus urticae* eggs. Points show the percentage of individuals consumed or killed by the predator at each level of initial prey density.

populations were similar, ranging from 67% to 79% of *T. urticae* eggs. The proportion of prey consumed by *A. swirskii* females in both NP and RP populations decreased as prey density increased (Table 2, Figure 2 and 3).

Table 2 Mean \pm SE daily predation rates of NP and RP populations of *Amblyseius swirskii* at varying *Tetranychus urticae* egg densities.

Prey density	Populations / Treatments	Number of prey consumed (Ne) (Mean \pm SE)	Ne/No** (Mean \pm SE)	Df. F. P
5	NP Untreated ^a	3.73 \pm 0.30a*	74.67 \pm 6.01	3,59; 5.01; <0.01
	NP Acaricide treated ^b	2.80 \pm 0.26ab	56.00 \pm 5.24	
	RP Untreated ^c	4.40 \pm 0.29ab	88.00 \pm 5.80	
	RP Acaricide treated ^d	3.66 \pm 0.32b	73.33 \pm 6.38	
10	NP Untreated ^a	6.07 \pm 0.47bc	60.67 \pm 4.73	3,59; 11.03; <.001
	NP Acaricide treated ^b	5.00 \pm 0.28c	50.00 \pm 2.76	
	RP Untreated ^c	9.93 \pm 0.38a	79.33 \pm 3.84	
	RP Acaricide treated ^d	7.20 \pm 0.39ab	72.00 \pm 3.84	
20	NP Untreated ^a	11.80 \pm 0.46b	59.00 \pm 2.29	3,59; 12.99; <0.01
	NP Acaricide treated ^b	10.20 \pm 0.73b	51.00 \pm 3.63	
	RP Untreated ^c	14.60 \pm 0.57a	73.00 \pm 2.84	
	RP Acaricide treated ^d	14.13 \pm 0.49a	70.67 \pm 2.48	
40	NP Untreated ^a	23.80 \pm 0.79b	59.50 \pm 1.99	3,59; 12.81; <0.01
	NP Acaricide treated ^b	21.27 \pm 0.81b	53.16 \pm 2.02	
	RP Untreated ^c	31.00 \pm 1.62a	77.50 \pm 4.05	
	RP Acaricide treated ^d	28.93 \pm 1.55a	72.33 \pm 3.86	
80	NP Untreated ^a	65.40 \pm 1.00a	81.75 \pm 1.25	3,59; 6.58; <0.01
	NP Acaricide treated ^b	60.07 \pm 0.90ab	75.10 \pm 1.12	
	RP Untreated ^c	54.13 \pm 2.84b	67.66 \pm 3.54	
	RP Acaricide treated ^d	54.87 \pm 2.61b	68.58 \pm 3.26	

^a Acaricide-untreated natural population

^b Natural population treated with the recommended concentration of bifenthrin and abamectin

^c Acaricide-untreated resistant population

^d Resistant population treated with the recommended concentration of bifenthrin and abamectin

* In the ANOVA analysis, for treatments where significant differences were detected, different letters in the same column indicate statistically significant differences between means at the 1% significance level according to the Tukey test.

The treated and untreated RP populations exhibited a higher attack rate coefficient (α) compared to the treated and untreated NP populations across all prey densities. The highest attack rate (α) was observed in the untreated RP population (1.27 ± 0.18), followed by the treated RP population (1.13 ± 0.21), the untreated NP population (1.00 ± 0.14), and the treated NP population (0.71 ± 0.08). However, the differences between populations and treatments were not statistically significant. While *A. swirskii* individuals from the RP population exhibited a higher attack rate on prey than those from the NP population, this difference was not statistically significant ($P = 0.17$). The handling time (T_h) of RP populations was significantly shorter across all prey densities compared to NP populations. The shortest handling time (T_h) among all populations was observed in the untreated RP population (0.0376 ± 0.0019), followed by the treated RP population (0.0381 ± 0.0018), the treated NP population (0.0420 ± 0.0007), and the untreated NP population (0.0454 ± 0.0007) (Table 3). The prey handling time of the predatory mite varied significantly across treatments ($P < 0.01$). The longest prey handling time was observed in the NP population treated with acaricide, whereas the shortest was recorded in the treated RP population. However, no significant differences were found in the prey handling time between the treated and untreated RP populations or between the untreated NP population and the treated RP population, regardless of acaricide treatment.

Table 3 Mean \pm SE of attack rate and handling time for NP and RP populations of *Amblyseius swirskii* on different prey densities of *Tetranychus urticae* eggs.

Populations/Treatments	α (h ⁻¹)	T_h (h)
NP Untreated	1.00 \pm 0.14a*	0.0454 \pm 0.0007ab
NP Acaricide treated	0.71 \pm 0.08a	0.0420 \pm 0.0007a
RP Untreated	1.27 \pm 0.18a	0.0376 \pm 0.0019b
RP Acaricide treated	1.13 \pm 0.21a	0.0381 \pm 0.0018b
Df. F. P	3,11; 2.19; 0.17	3,59; 6.61; <0.01

^a Acaricide-untreated natural population

^b Natural population treated with the recommended concentration of bifenthrin and abamectin

^c Acaricide-untreated resistant population

^d Resistant population treated with the recommended concentration of bifenthrin and abamectin

The values α , attack rate; T_h , handling time

* In the ANOVA analysis, for treatments where significant differences were detected, different letters in the same column indicate statistically significant differences between means at the 1% significance level according to the Tukey test

Prey consumption during longevity of females and males

The variations in prey consumption by *A. swirskii* females across all biological stages were statistically significant among different treatments and populations (Table 4). The lowest consumption levels were observed in the treated NP population during the deutonymph and adult stages, followed by the untreated NP population. No significant differences in prey consumption were observed between the untreated and treated RP populations, except during the deutonymph stage.

Similarly, the differences in prey consumption by *A. swirskii* males across all biological stages were also significant among different treatments and populations (Table 5). In particular, the lowest *T. urticae* egg consumption was recorded in the treated NP population during the deutonymph and adult stages. However, no significant differences were observed in prey consumption among the untreated NP population and the treated and untreated RP populations.

Table 4 Mean±SE prey consumption of *Tetranychus urticae* eggs by females of *Amblyseius swirskii* NP and RP populations at different life stages (number).

Populations / Treatments	Larvae	Protonymph	Deutonymph	Adult (female)
NP Untreated ^a	2.72±0.30a*	9.20±0.45a	29.61±0.75c	121.48±1.35b
NP Acaricide treated ^b	2.67±0.24a	6.74±0.40b	16.71±0.65d	17.29±0.83c
RP Untreated ^c	2.95±0.28a	6.73±0.28b	36.82±0.65a	133.50±2.44a
RP Acaricide treated ^d	3.05±0.26a	6.86±0.37b	32.81±0.55b	131.52±1.75a
Df. F. P	3,111; 0.39; 0.76	3,101; 5.95; <0.01	3,95; 112.81; <0.01	3,90; 840.09; <0.01

^a Acaricide-untreated natural population

^b Natural population treated with the recommended concentration of bifenazate and abamectin

^c Acaricide-untreated resistant population

^d Resistant population treated with the recommended concentration of bifenazate and abamectin

* In the ANOVA analysis, for treatments where significant differences were detected, different letters in the same column indicate statistically significant differences between means at the 1% significance level according to the Tukey test

Numerical response

When examining egg-laying performance, the lowest number of eggs was observed in the NP population treated with acaricide (1.93 ± 0.18) at the highest prey density (80 prey), followed by the untreated NP population (2.13 ± 0.24), the treated RP population (3.67 ± 0.29), and the untreated RP population (4.27 ± 0.21), respectively. Similar significant differences were observed at prey densities of 20 and 40 ($P = 0.02$ and $P < 0.01$, respectively). At the lowest prey densities (5 and 10), the differences among populations and treatments were insignificant ($P = 0.30$ and $P = 0.18$, respectively). The divergence between the curves became more pronounced after a prey density of 20, with treated and untreated RP populations exhibiting the highest egg-laying rates (Figure 4).

Discussion

Functional response is a commonly used tool for understanding the interaction between prey and predators (Kasap and Atlihan 2011). However, determining the functional response type of a predator in combination with a pesticide is a valuable approach for evaluating the toxicity of these compounds (Shen *et al.* 2017). In the present study, both resistant and native populations of *A. swirskii* exhibited a type II functional response when preying on *T. urticae* eggs. The type II functional response model is characterized by a decelerating predation curve that reaches a

Table 5 Mean±SE prey consumption of *Tetranychus urticae* eggs by males of *Amblyseius swirskii* NP and RP populations at different life stages (number).

Populations / Treatments	Larvae	Protonymph	Deutonymph	Adult (male)
NP Untreated ^a	1.67±0.42b*	11.50±0.76a	31.00±1.59a	89.50±0.65a
NP Acaricide treated ^b	2.50±0.65b	7.50±1.71b	14.75±1.93b	16.25±1.03b
RP Untreated ^c	4.20±0.36a	7.10±0.43b	35.50±0.65a	79.20±1.95a
RP Acaricide treated ^d	2.50±0.27b	7.20±0.33b	35.90±1.59a	78.50±11.66a
Df. F. P	3,29; 8.62; <0.01	3,29; 9.75; <0.01	3,29; 32.84; <0.01	3,29; 9.27; <0.01

^a Acaricide-untreated natural population

^b Natural population treated with the recommended concentration of bifenazate and abamectin

^c Acaricide-untreated resistant population

^d Resistant population treated with the recommended concentration of bifenazate and abamectin

* In the ANOVA analysis, for treatments where significant differences were detected, different letters in the same column indicate statistically significant differences between means at the 1% significance level according to the Tukey test.

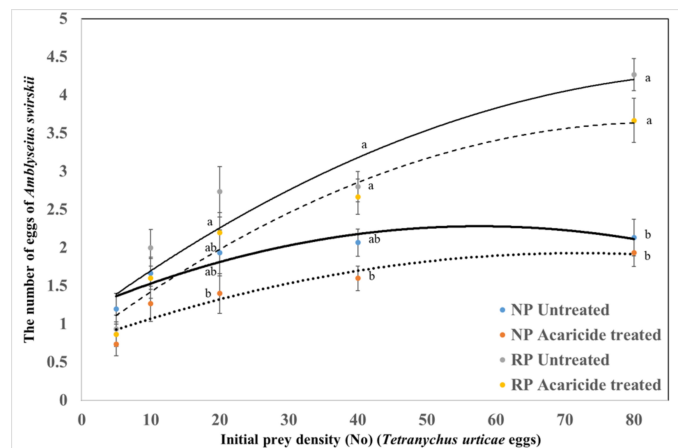


Figure 4 Numerical response of adult females of *Amblyseius swirskii* feeding on *Tetranychus urticae* eggs. Points represent the average number of eggs laid by the predator at each initial prey density level. Error bars indicate standard errors. In the ANOVA analysis, for treatments where significant differences were detected, different letters in the same prey density indicate statistically significant differences between means at the 1% significance level according to the Tukey test. There is no significant difference between 5 and 10 prey densities ($P > 0.05$).

plateau as prey density increases, acting as a destabilizing factor in predator-prey dynamics (Hassell *et al.* 1977). Previous studies have demonstrated that *A. swirskii* exhibits a type II functional response when feeding on different biological stages of spider mites (Fathipour *et al.* 2020; Shirvani *et al.* 2023; Elmoghazy *et al.* 2024). Similarly, a study of using as prey *Bemisia tabaci* (Genn.) (Hemiptera: Aleyrodidae) reported that *A. swirskii* also exhibited a type II functional response (Golshan *et al.* 2023). The type II functional response is commonly seen in several phytoseiid species, including *Chiloseius camposi* (González & Schuster) (Sepúlveda and Carrillo 2008), *Phytoseius plumifer* (Canestrini and Fanzago) (Kouhjeni Gorji *et al.* 2009), *Phytoseiulus persimilis* (Athias-Henriot) (Seiedy *et al.* 2012), *Neoseiulus barkeri* (Hughes), *Euseius nicholsi* (Ehara & Lee) (Yao *et al.* 2014), *Neoseiulus cucumeris* (Oudemans), *Neoseiulus californicus* (McGregor), *Neoseiulus longispinosus* (Evans) (Song *et al.* 2016), *Neoseiulus bicaudus* (Wainstein) (Zhang *et al.* 2017), and *Euseius concordis* (Chant) (da Silveira *et al.* 2020). At higher prey densities, the proportion of prey consumed decreased, likely due to predator satiation or interference, both of which reduce predation efficiency (Holling 1959; Park *et al.* 2011; Carrillo and Pena 2012; Bazgir *et al.* 2018). The results indicated that feeding increased linearly at low to medium prey densities but plateaued upon reaching maximum satiation. These findings suggest that the predatory efficiency of this species is enhanced when *T. urticae* egg densities are from low to moderate. Similar results have been reported by Xiao *et al.* (2013) and Farazmand and Amir-Maafi (2021).

The functional responses of predators can shift from one type to another depending on environmental conditions or pesticide treatments (Mohaghegh *et al.* 2001; Li *et al.* 2006; Afshar and Latifi 2017; Afza *et al.* 2021). In the present study, exposure to the recommended concentration of the acaricide (abamectin and bifentazate mixture) changed the functional response of the native *A. swirskii* population from type II to type III. In contrast, when exposed to the same acaricide, the resistant population maintained a type II functional response. Similarly, Afza *et al.* (2021) found comparable results, reporting that the functional response of *Coccinella septempunctata* L. (Coleoptera: Coccinellidae) shifted from type II to type III following the application of imidacloprid, profenophos, and chlorpyrifos with sublethal concentrations. Similarly, a shift from type II to type III in the functional response of *Scolothrips takahashii* Priesner (Thysanoptera: Thripidae) was reported in the sublethal concentration of abamectin exposure (Li *et al.* 2006). Moreover, Gu (1991) showed that the functional response

of *Diaeretiella rapae* M'Intosh (Hymenoptera: Aphidiidae) changed from type II to type III after exposure to cypermethrin, dimethoate and pirimicarb. In contrast to our findings, sublethal concentrations of bifentazate did not affect on the functional response of different biological stages of *N. bicaudus* preying on *Tetranychus turkestanii* Ugarov & Nikolski (Acarid: Tetranychidae) (Shen *et al.* 2017). In the current study, this shift in functional response may be attributed to unconsciousness and disorientation induced by abamectin, which targets the insect nervous system (Li *et al.* 2006). On the other hand, our findings indicate that the type of functional response of the *A. swirskii* population, which developed resistance to both abamectin and bifentazate, remained Type II after exposure to the recommended concentration of the acaricide.

The attack rate and handling time are two key parameters used to assess the magnitude of functional responses (Pervez and Omkar 2006). Handling time is a key indicator of consumption rate and predator efficiency. It represents the total time required for capturing, killing, and digesting prey (Veeravel and Baskaran 1997a,b). It can be influenced by predator speed, prey movement, and the time required to subdue prey, which may relate to behavioral and structural defense mechanisms (Hassell 1978; Ali *et al.* 2011). At varying densities of *T. urticae* eggs, the mean attack rate (α) and handling time (Th) of adult female *A. swirskii* were measured. In the native population, α and Th were 1.00 and 0.0454, respectively, while in the resistant population, they were 1.27 and 0.0376. Fathipour *et al.* (2017b) reported a handling time of 1.387 for *A. swirskii*, with its functional response identified as both type II and type III. Afshar and Latifi (2017) observed a type III response at 25 °C, and type II at 30 and 35 °C; handling time ranged from 0.46 to 0.6, while the attack rate (α) was 0.56. Golshan *et al.* (2023) estimated α and Th as 0.106 and 0.353, respectively, when *A. swirskii* fed on different developmental stages of *B. tabaci*, and reported a type II functional response. The results are largely consistent with previous studies, with observed differences likely attributed to variations in experimental temperatures, absence of pesticide application, and the use of different host plants or prey species. In the present study, following acaricide application, these values were 0.71 and 1.13 for α , and 0.0420 and 0.0381 for Th in native and resistant populations of *A. swirskii*, respectively. Although the attack rate in the native population did not differ significantly, a slight decrease was observed. However, handling time was significantly prolonged compared to the untreated native population, indicating a potential impact on predation efficiency. In contrast, neither of the key parameters was affected in the resistant population after exposure to the acaricide. Similar adverse effects have been reported following exposure to sublethal concentrations of certain pesticides. These effects include reduced attack rates and prolonged handling times in several predator species (Wang and Shen 2002; Claver *et al.* 2003; Li *et al.* 2006).

One of the significant limitations of functional response studies is that they are typically conducted over a short period, often lasting only two days, which does not represent the predator's entire lifespan. Therefore, in this study, the prey consumption of *A. swirskii* was monitored from the larval stage until the death of the adult. This approach allowed for a more comprehensive assessment of the effects of the acaricide on prey consumption over an extended period. In the present study, the number of prey consumed (number of eggs) by female *A. swirskii* that were not treated with the acaricide was very similar in both the natural and resistant populations. Following acaricide application, prey consumption significantly decreased in the native population compared to the untreated conditions. Similar to other biological parameters, prey consumption in the resistant population slightly increased compared to the natural population, and no reduction was observed in the resistant population after acaricide exposure.

Momen and Elsaway (1993) reported that female predators consumed 15 to 125 *T. urticae* individuals per day. Yan-Xuan and Jian-Zhen (2011) documented a daily prey consumption rate of 57.6 eggs per female. Maroufpoor (2017) recorded average predation rates on eriophyid and spider mites as 183 and 420 individuals per day, respectively. Golshan *et al.* (2023) observed that female mites laid an average of 67.91 eggs per day. These findings are largely

consistent with our results. In general, the consumption rate of a predator decreases as the size of the prey's life stage increases (Ali *et al.* 2011; Fathipour *et al.* 2017b; Bazgir *et al.* 2018). *Amblyseius swirskii* consumed *T. urticae* eggs at a higher rate compared to other developmental stages (Soleymani *et al.* 2016a,b).

Conclusion

In conclusion, the abamectin and bifenazate mixture acaricide is relatively safe for the resistant population of *A. swirskii*. This finding suggests that resistance mechanisms are crucial in maintaining functional response stability. These findings provide valuable insights into the ecological impact of acaricides on predatory mites. Although laboratory-based functional response studies offer valuable insights into predator-prey interactions and arthropod population dynamics, they have limitations when applied to natural conditions. Factors such as artificially high prey densities, absence of natural barriers like webbing, and lack of multispecies interactions can magnify predation efficiency. The compatibility of the resistant population with acaricide-treated environments highlights their potential for use in IPM programs (Liang *et al.* 2015; Bielza 2016; Tabashnik *et al.* 2018). The use of resistant *A. swirskii* appears compatible with biological control and IPM programs. Therefore, while the findings support future studies and management strategies for *T. urticae*, field-based research is essential to accurately assess the biocontrol potential under realistic environmental conditions.

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