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Research Article

Efficacy of *Psyllaephagus pistaciae* (Hymenoptera: Encyrtidae) as a biocontrol agent against *Agonoscena pistaciae* (Hemiptera: Aphalaridae) using age-specific functional response

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Abstract. *Psyllaephagus pistaciae* (Hymenoptera: Encyrtidae) is the primary native biocontrol agent targeting the common pistachio psylla, *Agonoscena pistaciae* (Hemiptera: Aphalaridae), a major pest in Rafsanjan, the leading pistachio production region in Iran. In this study, how female parasitoid age influences the type of functional response was examined by daily assessing two behavioral traits—host feeding and parasitism—across different densities of pistachio psylla, within the context of age-specific functional response. The logistic regression analysis identified a type II functional response for *P. pistaciae*, characterized by an increased attack rate (parasitism + host feeding) with increasing psylla density. Notably, this response pattern was consistent across different female ages. In the first week of adulthood, wasps demonstrated optimal searching efficiency for both parasitism and host feeding. However, as female wasps aged, there was a progressive increase in handling time for parasitism and feeding activities. Peak searching efficiency for host attacks was observed on day 7, while the minimum handling time occurred on day 5. The highest levels of parasitism were observed on the fifth day of the female's lifespan, underscoring increased efficiency in parasitism and attack rates during the early stages of the parasitoid's life, especially within the first week. Moreover, both host density and parasitoid age significantly affected these rates.

Keywords: Biological control, parasitoids, host-feeding, host densities, parasitism

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Introduction

The common pistachio psylla (CPP), *Agonoscena pistaciae* Burckhardt and Lauterer (Hemiptera: Aphalaridae), is a notable pest of cultivated pistachio trees, *Pistacia vera* L., in Iran and neighboring pistachio-growing regions (Burckhardt & Lauterer, 1993; Mehrnejad, 2001). Elevated population density during the kernel development phase from June to August results in substantial reductions in pistachio yield and tree vigor for three consecutive years (Mehrnejad & Jalali, 2004). The parasitoid *Psyllaephagus pistaciae* Ferrière (Hymenoptera: Encyrtidae) operates as a specific, solitary, koinobiont endoparasitoid (allowing host to continue development after parasitism) of *A. pistaciae* nymphs and serves as the exclusive primary parasitoid of *A. pistaciae* in pistachio plantation areas in Iran, operational from April to November (Mehrnejad, 1998; Mehrnejad & Emami, 2005). Furthermore, besides parasitism, host-feeding behavior characterizes synovigenic insects (maturing eggs throughout its adult life), leading to a higher host population destruction, enhanced fecundity and longevity, and a significant contribution to their fitness.

Understanding parasitoid foraging behavior is crucial for assessing their impact on host populations and reproductive success within a given environment (Chavarín-Gómez *et al.*, 2023; Wajnberg *et al.*, 2008). Researchers in applied ecology and biological control aim to understand various aspects of host-parasitoid interactions. These include the parasitoid's functional response to host densities, variations in searching efficiency associated with female age, and the impact of host-feeding behavior (Berryman, 1999; Lester & Harmsen, 2002). A significant portion of adult parasitoids engage in host-feeding, which plays a vital role in their reproductive success (Bernstein & Jervis, 2008; Zhang *et al.*, 2022). This trait is characteristic of syn-ovigenic parasitoids (koinobiont parasitoids) and is prevalent within this group (Kidd & Jervis, 1989). The functional response serves as a tool to investigate natural enemy population control, particularly when it's density-dependent (Murdoch & Oaten, 1975). It describes how a natural enemy responds to changes in the density of its prey (Holling, 1959b; Juliano *et al.*, 2022). The term 'functional response' was first introduced by Solomon to describe the fundamental aspects of predator-prey interactions (Solomon, 1949). Subsequently, Holling developed a fundamental model, known as the 'disc equation,' which captured prey consumption by a predator through a non-linear function of initial prey density and available time (Holling, 1959a). Building on earlier research (Royama, 1971), Rogers and Hassell later introduced an alternative model for sampling without replacement (Rogers, 1972; Rogers & Hassell, 1974). A type II functional response exhibits an initial rise in the number of attacked hosts per parasitoid as prey density increases, followed by an eventual plateau. Conversely, the type III of functional response demonstrates an initial rise in attack rate with increasing prey density, followed by a decline, resulting in a sigmoid functional response curve (Oaten & Murdoch, 1975). Type II and III functional responses are commonly observed among arthropod predators and parasitoids (Van Lenteren & Bakker, 1977). Assessments of these responses are frequently carried out to evaluate their potential effects on the growth and decline of host populations (Oaten & Murdoch, 1975).

Studying functional responses requires understanding how different factors affect the type of response and its key measures, like handling time and attack rate, which may be impacted by a variety of factors. Abiotic factors include temperature, humidity, pesticides, experimental conditions, and the unit of measurement. Biotic factors, including the host plant, life cycle stage, age, sex, developmental phase, availability of alternate diets, generation, and spatial extent of natural enemies, significantly impact these responses. Moreover, the species of the host and the conditions of the host plant can further affect the type and parameters of the functional response (Dalir *et al.*, 2021; Jalali *et al.*, 2010; Jalali & Ziaaddini, 2017; Rezaei *et al.*, 2021) .

A review of the current literature reveals no prior investigations into the functional response of *P. pistaciae*, a promising biological control candidate for CPP. Identifying the stage at which *P. pistaciae* demonstrates peak searching efficiency and minimal handling time could provide valuable insights into its behavioral ecology and interaction with host densities. This study hypothesizes that the age of the parasitoid *Psyllaephagus pistaciae* significantly influences key parameters of its functional response, specifically searching efficiency (a') and handling time (T_h), and possibly the type of functional response itself, across various host densities of *Agonoscena pistaciae*.

Materials and methods

Plant cultivation

Badami pistachio seeds, which can support and sustain pest populations, were sourced from the Pistachio Research Center. The seeds underwent a 24-hour water immersion and were then surface-sterilized with 1% sodium hypochlorite for 1 minute. Subsequently, germination took place between moistened paper towels, after which the seedlings were transplanted into 12 cm x 9 cm plastic pots filled with a mixture of garden soil, sand, and peat humus mixture. The seedlings were watered as necessary and received biweekly fertilization with a balanced 20-20-20 NPK solution. They were cultivated in a growth chamber set at a temperature of 27±1°C, a relative humidity of 60±10%, and a photoperiod of 16:8 (L: D). For infestation experiments, one-month-old seedlings were exposed to adult pistachio psyllids inside a cage covered with netting. Additionally, some seedlings were placed in a separate cage located 3 meters away from the infested plants, serving as controls to obtain healthy leaves. Pest populations on the healthy seedlings were managed through manual leaf cleaning, without the use of pesticides in the plant cultivation environment (Moghbeli *et al.,* 2013).

Stock Cultures of the Pest and Parasitoid

The initial population of pistachio psyllids was gathered in 2020 from orchards in Rafsanjan county, where pesticide applications had not occured, as well as from abandoned orchards. These specimens were then moved to a growth chamber maintained at a temperature of 27±1°C, a relative humidity of 60±10%, and a photoperiod of 16:8 (L: D) for breeding and propagation. Infestation of pistachio seedlings were conducted within enclosed cages outfitted with fine-mesh (organdy) nets.

For the experiments, the requisite population was selected from the third generation post-establishment, following a full observation of the insect's life cycle (egg, nymph, and adult) (Guedot *et al.*, 2009; Skelley & Hoy, 2004). Leaves bearing mummified psyllid nymphs were harvested from infested pistachio trees and transferred to lidded plastic containers measuring 12×15 cm. Containers were covered with organdy nets. The collection of these wasps was carried out daily using an aspirator. The gathered wasps were identified and assembled (Mehrnejad & Copland, 2006a). *P. pistaciae* was identified using reliable sources and subsequently bred and multiplied under controlled conditions (temperature of 27.5±1°C, relative humidity of 50 to 60%, and photoperiod of 16:8 (L: D) on pistachio seedlings infested with psyllids. The parasitoids were exclusively fed honey water 24 hours prior to the experiments. To mitigate the effects of inbreeding within the pest and parasitoid populations, specimens were collected from the field twice annually (mid-spring and late summer for the pest, June and September for the wasp) and released into the colony (Moghbeli, 2013).

Estimating the Functional Response

This study investigated the impact of host density on parasitism and host-feeding behaviors throughout the adult lifespan of *Psyllaephagus pistaciae*. Newly emerged adult pairs of *P. pistaciae* (consisting of one male and one female) were introduced into rearing containers and provided with a 10% solution of water and honey for 24 hours. Eleven distinct host density levels (2, 4, 6, 8, 16, 24, 32, 40, 64, 80, and 100) comprising fourth instar nymphs of *Agonoscena pistaciae* were transferred into 50 ml Falcon tubes covered with netting. Each host density was exposed to only one mated female. To maintain experimental uniformity, female wasps with similar body sizes, particularly comparable similar hind tibia lengths, were chosen for the study (Mehrnejad & Copland, 2006a; Mehrnejad & Copland, 2006b). Each treatment was replicated ten times (Asadi *et al.*, 2012; Chong & Oetting, 2007; Qin *et al.*, 2023; Rezaei *et al.*, 2021).

A fresh pistachio leaf (*Pistacia vera*, Badami cultivar) measuring with an area of 12 cm^2 was placed inside each Falcon tube, with 2 ml of distilled water to uphold leaf turgor. The females were starved of hosts for 24 hours before exposure to the designated host densities. Post 24 hours exposure, the same parasitoids were moved to new Falcon tubes containing fresh hosts of the same density for daily subsequent exposures. At the conclusion of each 24-hour period, the psyllid nymphs were removed from the Falcon tube and processed as follows:

- Host Feeding: Hosts consumed by the parasitoid during the 24-hour exposure were identified based on observable indications such as flattened and desiccated appearances, and documented over a span of three days.

- Parasitism: The surviving psyllids were transferred into 3 cm diameter Petri dishes using a soft brush. These live psyllids in the Petri dishes were monitored daily for up to 15 days. Signs of parasitism, including mummification, discoloration, swelling, and the presence of parasitoid eggs or pupae within the psyllids, were documented under a binocular microscope.

Each Petri dish was equipped with a ventilation hole (1 cm diameter) in the lid, covered with netting (Ebrahimifar *et al.*, 2017). A circular disk cut from a fresh, fully developed pistachio leaf (*Pistacia vera*, cultivar Badami) was placed in a Petri dish with the lower side facing down on a water-agar medium with a concentration of 16 g/L. These leaf discs were replaced every two days to ensure freshness and optimal conditions. The Petri dishes were kept in a growth chamber set at 27 ± 1°C, 60 ± 10% relative humidity, and a photoperiod of 16:8 h (L:D) (Mehrnejad & Copland, 2006b).

Statistical analysis

Host-feeding and parasitism are interlinked behaviors that contribute to host mortality and lead to a significant reduction in host populations. In order to estimate the functional response and its key parameters, parasitism was analyzed separately as an indicator of parasitoid efficiency and then integrated with host-feeding to evaluate their collective influence on host population dynamics (Asadi *et al.*, 2012; Cabello *et al.*, 2024).

The type of functional response was determined by utilizing data from various host densities over the lifespan of female wasps, encompassing both parasitized hosts and attacked hosts (those that were parasitized and consumed). Logistic regression was then employed to estimate maximum likelihood using PROC CATMOD (SAS, 2011), following the recommendation of Juliano (Juliano, 2020). Initially, logistic regression was utilized to ascertain the type of functional response by regressing the ratio of prey consumed (N_a/N_0) against prey density (Equation 1).

$$\frac{Na}{N0} = \frac{\exp\left(P_0+P_1N_0+P_2N_0^2+P_3N_0^3\right)}{1+\exp(P_0+P_1N_0+P_2N_0^2+P_3N_0^3)} \qquad (1)$$

Where, N_a represents the number of attacked hosts and N_0 indicates the density of nymphs. The parameters P_0, P_1, P_2, and P_3 in Equation (1) represent the maximum-likelihood estimates of the intercept, linear, quadratic, and cubic coefficients, respectively. According to Juliano (2020) the signs of P_1 and P_2 can be utilized to determine the functional response type. A negative P_1 indicates a type II response, whereas a positive P_1 with a negative P_2 suggests a type III response. In a type II response, the slope is negative ($P_1 < 0$), indicating a decrease in attack rate as prey density increases. Conversely, a type III response shows a positive slope ($P_1 > 0$), indicating an initial increase in the attack rate. Non-significant P_1 values led to stepwise removal of cubic and quadratic coefficients until a significant difference between the linear coefficient (P_1) and zero was observed (Ge *et al.*, 2019; Jalali *et al.*, 2010; Mahdian *et al.*, 2006). The Generalized Linear Model (GLM) procedure. was utilized to estimate the values of P_0, P_1, P_2, and P_3 in the logistic regression model, revealing a type II functional response. Subsequently, Type II equation (2) for parasitoids was applied to estimate handling time (T_h) and searching efficiency (a') from the data (Rogers, 1972; Royama, 1971).

$$N_a = N_0\left[1+\exp\left(-\frac{a'\,TP_t}{1+a'T_h\,N_0}\right)\right] \qquad (2)$$

N_a represents the total number of attacked hosts (parasitized + eaten), while N_o signifies the initial host density. Searching efficiency is represented by a', T denotes the total experimental duration (24 h), and T_h represents the handling time per host, encompassing the period from host discovery to the completion of parasitism or feeding. P_t represents the quantity of parasitoids used. The maximum number of parasitized and attacked hosts was calculated by dividing the total duration (24 hours) by T_h. Nonlinear least squares regression analysis was employed to estimate the functional response parameters using PROC NLIN (Asadi *et al.*, 2012; Chong & Oetting, 2007; Ebrahimifar *et al.*, 2017; Qin *et al.*, 2023). The Statistical analysis of the functional response was carried out using SAS software. Using the General Linear Model (GLM) technique within the Statistical Analysis System (SAS) software (version 9.4), the main effects (host density and parasitoid age), and interaction effects (host density × parasitoid age) of experimental variables, were evaluated. The experiment followed a factorial design with two factors based on a completely randomized design (CRD). Different groups were compared using Tukey's HSD test at a significance level of $P < 0.05$. The interaction of age and density was examined using the slicing method, dividing the data into subsets post-ANOVA for significant interaction terms. This method, also known as simple effects or simple main effects, dissects two-way interaction by comparing host density and parasitoid age within specific age treatments. Similarly, the comparisons among the parasitoid age categories are based on the prey density levels at which they were conducted (Dalir *et al.*, 2021; Schabenberger *et al.*, 2000).

Results

Estimating Functional Response

The age-specific functional responses of *P. pistaciae*, concerning both parasitism and attack at varying levels of CPP, are illustrated in Fig. 1 and 2, respectively, illustrating the mean quantities of nymphs that were subjected to parasitism and attack, as predicted by Rogers' model, across different ages of the female parasitoid as the parasitoid's lifetime progresses, the average number of hosts that are parasitized and attacked at each density declines. Moreover, it was noted that there was a decrease in both the attack rate and the parasitization rate, which exhibited a correlation in relation to the density of the host and the age of the parasitoid. Fig. 3 shows the average number of nymphs killed by host-feeding at various ages of the female parasitoid.

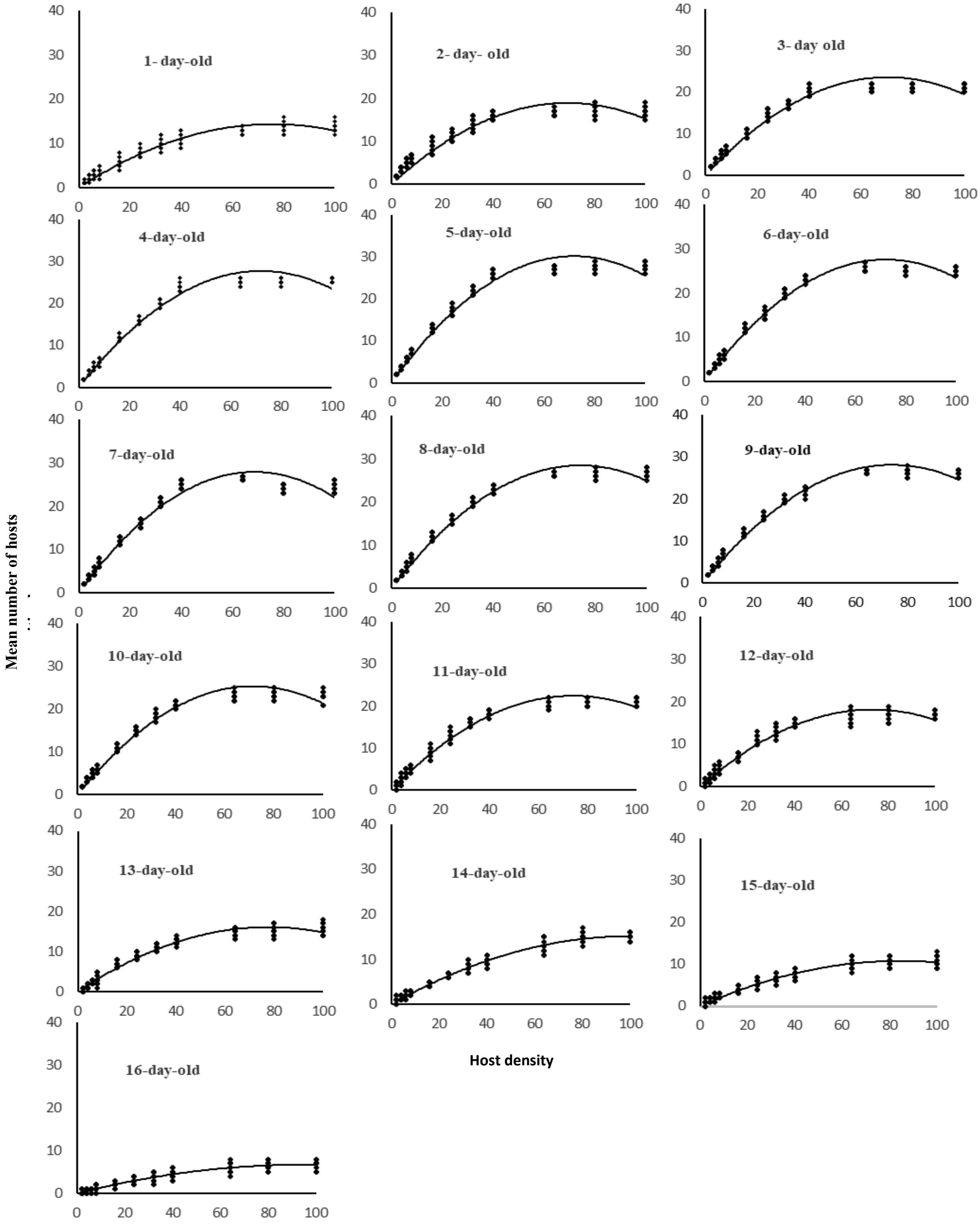

Fig. 1. Age-specific functional response of *P. pistaciae* in terms of parasitism at different densities of CPP

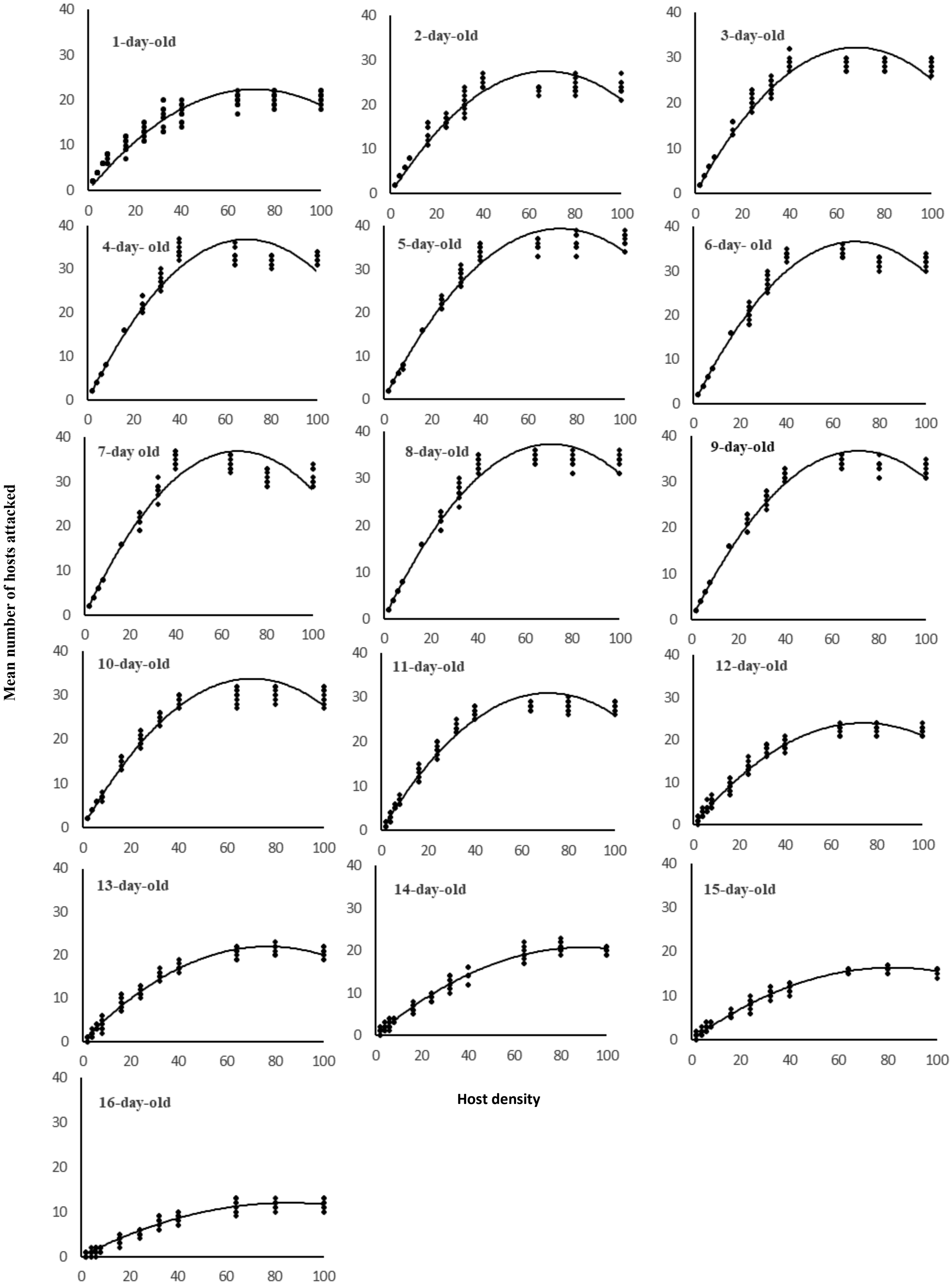

Fig. 2. Age-specific functional response of *P. pistaciae* in terms of attack at different densities of CPP.

As the parasitoid ages, the number of hosts exposed to host-feeding at each density decreases. Additionally, a decline in the host-feeding rate was observed, showing a correlation between host density and the parasitoid's age. For example, at a nymph density of 40, the average number of hosts parasitized by an adult female wasp was 11 on the first day, 26 on the fifth day, and 4.5 on the sixteenth day. The mean count of hosts attacked at the same nymph density showed an increasing trend up to the fifth day of the adult female's age, with estimates of 17.2, 34.4, and 8.6 on the first, fifth, and sixteenth day, respectively.

This trend was observed for both traits, parasitism and attack. After the seventh day, a decreasing trend was observed. Furthermore, the average count of parasitisms and host attacks escalated in correlation with host density over the entire lifespan of the parasitoid. As an example, on the fifth day of adult life, the average number of hosts parasitized ranged from 2 at a density of 2 to 27.7 at a density of 100, with intermediate values observed at increasing host densities (2, 3.80, 5.80, 7.50, 13, 17.20, 22, 26, 27, 27.5). Regression analyses revealed a positive correlation between the average number of parasitized hosts and host density at all three examined ages: the first day ($R^2 = 0.92$), the fifth day ($R^2 = 0.97$), and the sixteenth day ($R^2 = 0.89$) of adult female life. Conversely, regression analyses investigating the total number of attacked hosts against host density yielded quadratic equations for all three days: first day ($y = -0.0044x^2 + 0.6256x$, $R^2 = 0.89$), fifth day ($y = -0.0073x^2 + 1.0754x$, $R^2 = 0.97$), and sixteenth day ($y = -0.0016x^2 + 0.2793x$, $R^2 = 0.95$).

Data fitting to logistic regression revealed a significant negative linear coefficient (P_1) for hosts that were attacked (both parasitized and eaten). This suggests a Type II functional response, as indicated in Table 1. The functional response category remained unaffected by the age of the female parasitoid. The Rogers' type II equation was utilized under two distinct conditions throughout the lifespan of the female parasitoid. This was done to evaluate and compare the search efficiency and time spent handling at different ages of the female parasitoid. The estimated values of these two parameters are depicted in Table 2, explicitly searching efficiency and handling time, across the lifespan of *P. pistaciae.* The regression analysis indicated a significant association between the search efficiency (a') and handling time (T_h) in relation to the age of the female parasitoid. The maximum search efficiency (a') was recorded on the fifth day of the parasitoid's life for host parasitism (0.1535±0.00875 h^{-1}), and on the seventh day for host attacks (1.6912±0.8071 h^{-1}). Nonetheless, the peak value for a' was expected to occur within the first seven days of the adult female's lifespan. The a' value for hosts that were parasitized and attacked showed variations throughout the adult female's lifespan: it increased in the early days and then gradually decreased (Table 2). Handling time, which represents the time *P. pistaciae* spends on either parasitism or host feeding, showed a positive trend with the increasing age of the adult female for both behaviors. The minimum handling time for both parasitism and attack was observed on the fifth day of adult life. Following this, handling time generally rose gradually with minor fluctuations. The decline in parasitism rates with age further resulted in a steeper slope of the curve and an increase in handling time from the second week of adult life onwards (Table 2). The influence of the parasitoid's host-feeding behavior on two key functional response parameters, searching efficiency (a') and handling time (T_h), is evident across different parasitoid ages. Combining data on host feeding and parasitism behavior allows for visualization of their combined impact on these parameters, as detailed in Table 2. The variance analysis revealed a significant influence of both the age of the parasitoid and the density of the host on parasitism and attack, as well as an interaction between age and host density ($P < 0.0001$), as indicated in Table 3. The significant interactions were identified using the slicing method. During the lifespan of the parasitoid, there is a higher rate of parasitism and attack at densities of 40 and above, compared to lower densities (Table 4). According to Table 5, The rates of hosts that were parasitized and those that were attacked (parasitized + eaten) by *P. pistaciae* increased mainly up to the fifth day of the parasitoid's life and generally throughout the first week, across different densities of CPP nymphs and different ages of the parasitoid. Conversely, a decline in these rates is noticeable during the second week. At the highest host density (100 nymphs), the highest parasitism and attack rates were observed for 5-day-old parasitoids. In contrast, the lowest rates were observed at the beginning and end of the parasitoid's lifespan, showing a significant difference from other ages

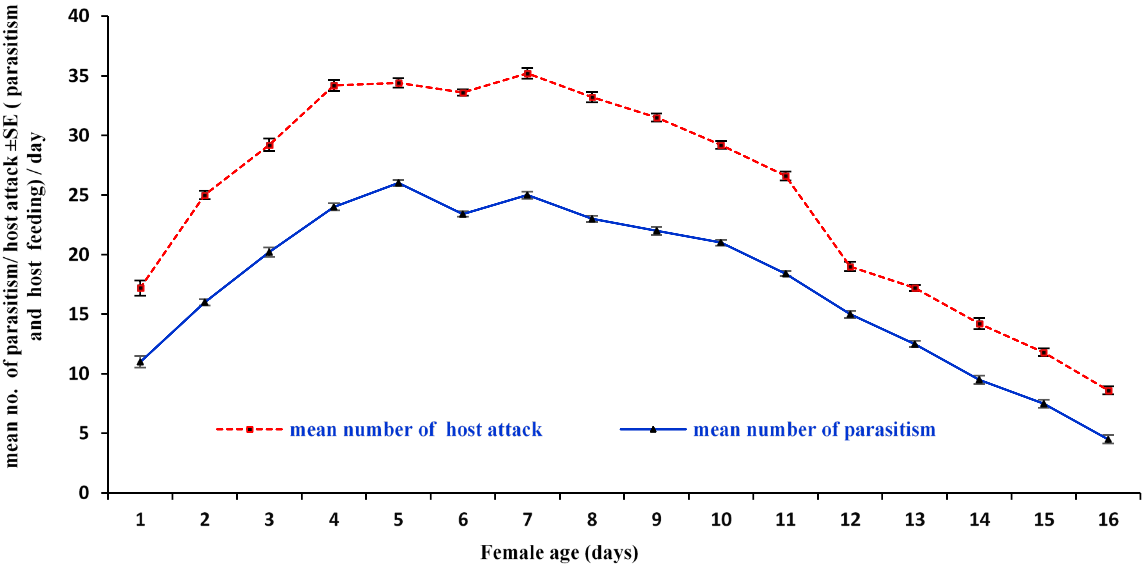

Fig. 3. Correlation between the average number of hosts parasitized and attacked to parasitoid age and host density (A: Density 40)

Table 1. The results of the maximum likelihood estimation analysis for the linear coefficient (P_1) of the logistic model. This model was used to fit the data related to the functional response type selected for *P. pistaciae* on the lifetime of adult females.

female parasitoid age (days)	linear coefficient (P_1) (mean ± SEM)	
	Hosts parasitized	Hosts attacked
1	-0.0176±0.0013	-0.1658± 0.0189
2	-0.1094± 0.0158	-0.1541±0.0229
3	-0.049±0.00574	-0.1771±0.0311
4	-0.0458± 0.00583	-0.1193±0.00947
5	-0.0638±0.0064	-0.116± 0.00963
6	-0.0425±0.00575	-0.0981±0.0086
7	-0.0435±0.00587	-0.1142±0.00957
8	-0.0493±0.00587	-0.1032±0.00883
9	-0.0494±0.00586	-0.186±0.0368
10	-0.0465±0.00574	-0.0771±0.00727
11	-0.025±0.00538	-0.0399±0.00595
12	-0.0182±0.00123	-0.0202±0.00117
13	-0.0148±0.00126	-0.0167±0.00117
14	-0.00949±0.0013	-0.0114±0.00118
15	-0.0134±0.00144	-0.0139±0.00125
16	-0.00884±0.0018	-0.00993±0.0014

Table 2. Evaluation of Functional Response Parameters (± SE): Search Efficiency (a) and Handling Time (T_h) in *P. pistaciae* Females of Various Ages, Utilizing the Estimated Rogers' Type II Equation

female parasitoid age	parasitism		R^2	mean number of parasitism		host attacked (parasitism and feeding)		mean number of host attack		Maximum number of hosts attacked
	a **(h^{-1})±SE**	**T_h (h)±SE**		**mean**	**SE**	***a*** **(h^{-1}) ±SE**	**T_h (h)±SE**	**mean**	**SE**	
1	0.034±0.00213	1.3794±0.0421	0.993	7.78	0.45	0.0939±0.00722	1.0306±0.023	12.5	0.64	23.29
2	0.0779±0.00527	1.2329±0.0249	0.977	10.7	0.53	0.1897±0.0195	0.9064±0.0171	15.2	0.82	26.48
3	0.0971±0.00542	0.9644±0.0159	0.979	12.9	0.71	0.3324±0.039	0.7911±0.0116	17.6	1	30.34
4	0.1196±0.0065	0.8102±0.0123	0.981	14.9	0.87	0.6932±0.1367	0.7038±0.0096	19.7	1.18	34.1
5	0.1535±0.00875	0.7633±0.0104	0.981	16.3	0.94	0.4577±0.0506	0.6243±0.0072	20.8	1.29	38.44
6	0.1107±0.00625	0.8011±0.0136	0.981	14.8	0.87	0.462±0.072	0.6863±0.0107	19.6	1.18	34.97
7	0.1482±0.0126	0.8457±0.0166	0.978	15.1	0.87	1.6912±0.8071	0.7247±0.0113	19.7	1.19	33.12
8	0.1087±0.00437	0.762±0.00959	0.992	15.3	0.9	0.4091±0.0484	0.6622±0.0088	19.9	1.21	36.24
9	0.1062±0.00422	0.7715±0.0096	0.994	15.1	0.88	0.3227±0.028	0.6601±0.0080	19.6	1.18	36.36
10	0.1008±0.00492	0.8777±0.013	0.988	13.8	0.78	0.2744±0.0237	0.7261±0.0096	18.1	1.07	33.05
11	0.0667±0.00343	0.9236±0.0189	0.987	11.9	0.73	0.1694±0.012	0.7526±0.0119	16.4	1	31.89
12	0.0486±0.00294	1.1224±0.0297	0.985	9.68	0.59	0.0728±0.00428	0.862±0.0197	12.7	0.79	27.84
13	0.0344±0.00182	1.1671±0.0333	0.987	8.36	0.54	0.0533±0.00294	0.874±0.0233	11.4	0.74	27.46
14	0.0172±0.00079	0.8589±0.0451	0.999	7.1	0.5	0.0305±0.00143	0.7187±0.0283	10.1	0.71	33.39
15	0.0174±0.00115	1.5607±0.0731	0.999	5.6	0.35	0.0289±0.00131	1.0429±0.0312	8.4	0.54	23.01
16	0.00778±0.00067	2.0919±0.1876	1	3.22	0.24	0.0168±0.00106	1.2666±0.0678	5.89	0.42	18.95

Table 3. Variance analysis of the effects of the parasitoid's age and host density on two traits (parasitism and attack) of *Psyllaephagus pistaciae* across various nymph densities of CPP

source	df	MS		F		P	
		parasitism	attack	parasitism	attack	parasitism	attack
Age	15	1787.61697	2457.0527	2148.72	2041.74	<.0001	<.0001
Density	10	8431.90545	16422.2114	10135.2	13646.4	<.0001	<.0001
Age*Density	150	63.85564	100.1811	76.75	83.25	<.0001	<.0001
Error	1584	0.8319	1.2034	----	----	----	----

Table 4. The daily hosts parasitized and hosts attacked (parasitized + eaten) (± SE) by *P. pistaciae* across varying densities of CPP nymphs are presented.

Age (d)	Density	Parasitism ± SE	Attack ± SE	Density	Age (d)	Parasitism ± SE	Attack ± SE
1	2	1.2± 0.13h	2h	9	2	2i	2j
	4	2.4±0.22g	4g		4	3.6±0.16h	4i
	6	3.2±0.25f	6f		6	5±0.26g	6h
	8	3.5±0.34f	7.5±0.27e		8	7±0.26f	8g
	16	6±0.47e	10.5±0.5d		16	12±0.26e	16f
	24	8±0.33d	13±0.45c		24	16±0.26d	21.1±0.53e
	32	10±0.47c	16.5±0.82b		32	19.8±0.25c	26.6±0.40d
	40	11±0.47b	17.2±0.63b		40	22±0.33b	31.5±0.34c
	64	13±0.26a	20±0.45a		64	26.3±0.15a	34.4±0.34a
	80	13.6±0.40a	20.5±0.45a		80	26.4±0.31a	33.4±0.48b
	100	13.7±0.37a	20.6±0.43a		100	26±0.26 a	33±0.45b
		(12-16)*	(18-22)*			(25-27)	(31-35)
2	2	2i	2i	10	2	2i	2i
	4	3.8±0.13h	4h		4	3.6±0.16h	4h
	6	5±0.26g	6g		6	5±0.26g	6g
	8	6±0.26f	8f		8	6±0.2f	7f
	16	9±0.47e	13.8±0.65e		16	11±0.26e	14.9±0.38e
	24	11±0.33d	16.3±0.30d		24	15±0.26d	20.1±0.43d
	32	14±0.52c	20.5±0.69c		32	18.5±0.27c	25.3±0.33c
	40	16±0.26b	25±0.37a		40	21±0.26b	29.2±0.33b
	64	16.5±0.22ab	23.7±0.21b		64	23±0.33a	30±0.52a
	80	17±0.45a	24±0.49b		80	23.5±0.34a	30.8±0.47a
	100	16.9±0.38 a	23.8±0.51b		100	23±0.39 a	30±0.54 a
		(15-19)	(21-27)			(21-25)	(27-32)
3	2	2i	2i	11	2	1±0.26i	1.3±0.15i
	4	3.6±0.16h	4h		4	2.5±0.34h	3.1±0.28h
	6	5±0.26g	6g		6	4±0.26g	5.2±0.13g
	8	6±0.26f	8f		8	5±0.2f	6.5±0.22f
	16	10±0.30e	15.2±0.42e		16	9±0.42e	12.7±0.47e
	24	14.8±0.39d	20.8±0.53d		24	13±0.45d	18.6±0.45d
	32	17±0.26c	23.5±0.54c		32	16±0.30	22.8±0.33c
	40	20.2±0.39b	29.2±0.53a		40	18.4±0.22b	26.6±0.37b
	64	21±0.26a	28.2±0.39b		64	20.4±0.34a	27.9±0.23a
	80	21.2±0.25a	28.2±0.39b		80	20.8±0.29a	28.1±0.38a
	100	21.3±0.26a	28.2±0.42b		100	21±0.30 a	28±0.33a
		(20-22)	(26-30)			(20-22)	(26-29)
4	2	2i	2i	12	2	1± 0.26i	1.2±0.20h
	4	3.6±0.16h	4h		4	2±0.21h	2.40±0.22g
	6	5±0.26g	6g		6	3.2±0.33g	3.9±0.28f
	8	6±0.26f	8f		8	4.2±0.29f	5.3±0.30e
	16	12±0.26e	16e		16	7±0.26e	9±0.47d
	24	16±0.26d	22±0.49d		24	11±0.33d	13.6±0.40c
	32	20±0.30c	27.3±0.52c		32	13±0.47c	18.2±0.33b
	40	24±0.30b	34.2±0.47a		40	15±0.30b	19±0.39b
	64	25±0.26a	32.9±0.50b		64	16.5±0.48a	22±0.37a
	80	25.1±0.23a	32.1±0.35b		80	16.7±0.45a	22.6±0.40a
	100	25.5±0.17 a	32.5±0.34b		100	16.9±0.23 a	22.2±0.33a
		(25-26)	(31-34)			(16-18)	(21-24)
5	2	2i	2j	13	2	0.4±0.16i	0.6±0.16h
	4	3.8±0.13h	4i		4	1.4±0.16h	1.8±0.20g
	6	5.8±0.13g	6h		6	2.4±0.16g	3.2±0.13f
	8	7.5±0.17f	7.9±0.10g		8	3±0.42g	4.1±0.43f
	16	13±0.26e	16f		16	7±0.26f	9±0.47e
	24	17.2±0.39d	22.1±0.35e		24	9±0.26e	11.6±0.31d
	32	22±0.26c	28.5±0.54d		32	11±0.26d	15.4±0.27c
	40	26±0.26b	34.4±0.40c		40	12.5±0.27c	17.2±0.25b
	64	27±0.26a	35.3±0.47bc		64	14.5±0.34b	20.4±0.43a
	80	27.5±0.34a	36.1±0.67ab		80	15.2±0.42ab	21.2±0.36a
Age (d)	**Density**	**Parasitism ± SE**	**Attack ± SE**		**Age (d)**	**Parasitism ± SE**	**Attack ± SE**
	100	27.7±0.37 a	36.6±0.54a		100	15.6±0.45 a	20.7±0.37a
		(26-29)	(34-39)			(14-18)	(19-22)
6	2	2i	2i	14	2	0.8±0.25i	1±0.21j
	4	3.6±0.16h	4h		4	1.5±0.17h	1.8±0.25ij
	6	5±0.26g	6g		6	2±0.21gh	2.5±0.31i
	8	6±0.26f	8f		8	2.5±0.17g	3.5±0.17h

	16	12±0.26e	16e		16	4.3±0.15f	6.3±0.30g
	24	15±0.33d	20.1±0.59d		24	6.3±0.15e	8.9±0.28f
	32	20±0.30c	27.3±0.52c		32	8.2±0.39d	12.6±0.48e
	40	23.4±0.22b	33.6±0.27a		40	9.5±0.34c	14.2±0.47d
	64	25.7±0.30a	33.9±0.35a		64	13±0.52b	19.1±0.50c
	80	25.1±0.23a	32.1±0.35b		80	15±0.37a	21±0.39a
	100	25.1±0.28 a	32.3±0.37b		100	15±0.26 a	20.1±0.28 b
		(24-26)	(30-34)			(14-16)	(19-21)
7	2	2j	2j	15	2	0.9±0.23h	1±0.21h
	4	3.6±0.16i	4i		4	1.5±0.17g	1.8±0.20gh
	6	5±0.26h	6h		6	2±0.21fg	2.7±0.26fg
	8	7±0.26g	8g		8	2.5±0.17f	3.3±0.15f
	16	12±0.26f	16f		16	4±0.26e	5.7±0.21e
	24	16±0.26e	21.1±0.53e		24	5.5±0.34d	7.9±0.41d
	32	21±0.26d	28.3±0.50d		32	6.5±0.34c	10.7±0.30c
	40	25±0.30b	35.2±0.44a		40	7.5±0.34b	11.8±0.33b
	64	26.3±0.15a	34.2±0.47b		64	10±0.42a	15.7±0.15a
	80	24±0.30c	31±0.52c		80	10.5±0.40a	16.1±0.23a
	100	24.2±0.39 c	31.2±0.59c		100	10.7±0.47 a	15.7±0.21a
		(23-26)	(29-34)			(9-13)	(14-16)
8	2	2i	2i	16	2	0.3±0.15f	0.4±0.16f
	4	3.6±0.16h	4h		4	0.6±0.16ef	0.9±0.18ef
	6	5±0.26g	6g		6	0.8±0.13ef	1.5±0.22e
	8	7±0.26f	8f		8	1.2±0.25e	1.7±0.15e
	16	12±0.26e	16e		16	2±0.21d	3.7±0.30d
	24	16±0.26d	21.1±0.53d		24	3±0.26c	5.3±0.21c
	32	20±0.26c	27.3±0.5c		32	3.8±0.39b	7.8±0.36b
	40	23±0.26b	33.2±0.44b		40	4.5±0.34b	8.6±0.34b
	64	26.3±0.15a	34.4±0.34a		64	6±0.39a	11.6±0.48a
	80	26.5±0.3a	33.5±0.50ab		80	6.5±0.34a	11.7±0.26a
	100	26.6±0.3 a	33.6±0.50ab		100	6.7±0.33 a	11.6±0.37 a
		(25-28)	(31-36)			(5-8)	(10-13)

Means followed by different letters within each column of each age are significantly different (P < 0.05, Tukey's test) .The values enclosed in parentheses indicate the range (minimum and maximum) of parasitism and attacks by *Psyllaephagus pistaciae* at the highest density of CPP's nymphs.

Table 5. Hosts parasitized and hosts attacked (parasitized + eaten) (± SE) over different densities of CPP nymphs by *P. pistaciae* of different ages.

Density	Age (d)	Parasitism ± SE	Attack ± SE	Density	Age (d)	Parasitism ± SE	Attack ± SE
2	1	1.2± 0.13b	2a	32	1	10±0.47j	16.5±0.82g
	2	2a	2a		2	14±0.52g	20.5±0.69e
	3	2a	2a		3	17±0.26e	23.5±0.54d
	4	2a	2a		4	20±0.30c	27.3±0.52b
	5	2a	2a		5	22±0.26a	28.5±0.54a
	6	2a	2a		6	20±0.30c	27.3±0.52b
	7	2a	2a		7	21±0.26b	28.3±0.50a
	8	2a	2a		8	20±0.26c	27.3±0.52b
	9	2a	2a		9	19.8±0.25c	26.6±0.40b
	10	2a	2a		10	18.5±0.27d	25.3±0.33c
	11	1±0.26bcd	1.3±0.15ab		11	16±0.30f	22.8±0.33d
	12	1± 0.26bcd	1.2±0.20ab		12	13±0.47h	18.2±0.33f
	13	0.4±0.16c	0.6±0.16b		13	11±0.26i	15.4±0.27h
	14	0.8±0.25bcd	1±0.21b		14	8.2±0.39k	12.6±0.48i
	15	0.9±0.23bcd	1±0.21b		15	6.5±0.34l	10.7±0.30j
	16	0.3±0.15d	0.4±0.16b		16	3.8±0.39m	7.8±0.36k
4	1	2.4±0.22b	4a	40	1	11±0.47l	17.2±0.63h
	2	3.8±0.13a	4a		2	16±0.26i	25±0.37f
	3	3.6±0.16a	4a		3	20.2±0.39g	29.2±0.53e
	4	3.6±0.16a	4a		4	24±0.30c	34.2±0.47b
	5	3.8±0.13a	4a		5	26±0.26a	34.4±0.40ab
	6	3.6±0.16a	4a		6	23.4±0.22cd	33.6±0.27bc
	7	3.6±0.16a	4a		7	25±0.30b	35.2±0.44a
	8	3.6±0.16a	4a		8	23±0.26d	33.2±0.44c
	9	3.6±0.16a	4a		9	22±0.33e	31.5±0.34d

	10	3.6±0.16a	4a		10	21±0.26f	29.2±0.33e
	11	2.5±0.34b	3.1±0.28a		11	18.4±0.22h	26.6±0.37f
	12	2±0.21bc	2.40±0.22bc		12	15±0.30j	19±0.39g
	13	1.4±0.16c	1.8±0.20cd		13	12.5±0.27k	17.2±0.25h
	14	1.5±0.17c	1.8±0.25cd		14	9.5±0.34m	14.2±0.47i
	15	1.5±0.17c	1.8±0.20cd		15	7.5±0.34n	11.8±0.33j
	16	0.6±0.16d	0.9±0.18d		16	4.5±0.34o	8.6±0.34k
6	1	3.2±0.25d	6a	64	1	13±0.26h	20±0.45ij
	2	5±0.26b	6a		2	16.5±0.22f	23.7±0.21g
	3	5±0.26b	6a		3	21±0.26e	28.2±0.39f
	4	5±0.26b	6a		4	25±0.26c	32.9±0.50d
	5	5.8±0.13a	6a		5	27±0.26a	35.3±0.47a
	6	5±0.26b	6a		6	25.7±0.30bc	33.9±0.35c
	7	5±0.26b	6a		7	26.3±0.15ab	34.2±0.47bc
	8	5±0.26b	6a		8	26.3±0.15ab	34.4±0.34ab
	9	5±0.26b	6a		9	26.3±0.15ab	34.4±0.34ab
	10	5±0.26b	6a		10	23±0.33d	30±0.52e
	11	4±0.26c	5.2±0.13a		11	20.4±0.34e	27.9±0.23f
	12	3.2±0.33d	3.9±0.28b		12	16.5±0.48f	22±0.37h
	13	2.4±0.16e	3.2±0.13b		13	14.5±0.34g	20.4±0.43i
	14	2±0.21e	2.5±0.31c		14	13±0.52h	19.1±0.50j
	15	2±0.21e	2.7±0.26c		15	10±0.42i	15.7±0.15k
	16	0.8±0.13f	1.5±0.22d		16	6±0.39j	11.6±0.48l
8	1	3.5±0.34de	7.5±0.27ab	80	1	13.6±0.40h	20.5±0.45a
	2	6±0.26b	8a		2	17±0.45f	24±0.49b
	3	6±0.26b	8a		3	21.2±0.25e	28.2±0.39c
	4	6±0.26b	8a		4	25.1±0.23c	32.1±0.35d
	5	7.5±0.17a	7.9±0.10ab		5	27.5±0.34a	36.1±0.67e
	6	6±0.26b	8a		6	25.1±0.23c	32.1±0.35f

Density	Age (d)	Parasitism ± SE	Attack ± SE	Density	Age (d)	Parasitism ± SE	Attack ± SE
	7	7±0.26a	8a		7	24±0.30d	31±0.52g
	8	7±0.26a	8a		8	26.5±0.34b	33.5±0.50h
	9	7±0.26a	8a		9	26.4±0.31b	33.4±0.48h
	10	6±0.2b	7bc		10	23.5±0.34d	30.8±0.47i
	11	5±0.2c	6.5±0.22c		11	20.8±0.29e	28.1±0.38j
	12	4.2±0.29d	5.3±0.30d		12	16.7±0.45f	22.6±0.40k
	13	3±0.42ef	4.1±0.43e		13	15.2±0.42g	21.2±0.36l
	14	2.5±0.17f	3.5±0.17e		14	15±0.37g	21±0.39m
	15	2.5±0.17f	3.3±0.15e		15	10.5±0.40i	16.1±0.23n
	16	1.2±0.25g	1.7±0.15f		16	6.5±0.34j	11.7±0.26o
16	1	6±0.47g	10.5±0.54e	100	1	13.7±0.37 j	20.6±0.43 i
	2	9±0.47e	13.8±0.65c		2	16.9±0.38 h	23.8±0.51g
	3	10±0.30d	15.2±0.42a		3	21.3±0.26 g	28.2±0.42 f
	4	12±0.26b	16a		4	25.5±0.17 cd	32.5±0.34 c
	5	13±0.26a	16a		5	27.7±0.37 a	36.6±0.54 a
	6	12±0.26b	16a		6	25.1±0.28 d	32.3±0.37 c
	7	12±0.26b	16a		7	24.2±0.39 e	31.2±0.59 d
	8	12±0.26b	16a		8	26.6±0.3 b	33.6±0.50 b
	9	12±0.26b	16a		9	26±0.26 bc	33±0.45 bc
	10	11±0.26c	14.9±0.38b		10	23±0.39f	30±0.54 e
	11	9±0.42e	12.7±0.47d		11	21±0.30 g	28±0.33 f
	12	7±0.26f	9±0.47f		12	16.9±0.23 h	22.2±0.33 h
	13	7±0.26f	9±0.47f		13	15.6±0.45 i	20.7±0.37 i
	14	4.3±0.15h	6.3±0.30g		14	15±0.26 i	20.1±0.28 i
	15	4±0.26h	5.7±0.21g		15	10.7±0.47 k	15.7±0.21 j
	16	2±0.21i	3.7±0.30h		16	6.7±0.33 l	11.6±0.37 k
24	1	8±0.33g	13±0.45g				
	2	11±0.33e	16.3±0.30f				
	3	14.8±0.39c	20.8±0.53cd				
	4	16±0.26b	22±0.49ab				
	5	17.2±0.39a	22.1±0.35a				
	6	15±0.33c	20.1±0.59d				
	7	16±0.26b	21.1±0.53bc				
	8	16±0.26b	21.1±0.53bc				
	9	16±0.26b	21.1±0.53bc				
	10	15±0.26c	20.1±0.43d				

11	13±0.45d	18.6±0.45e
12	11±0.33e	13.6±0.40g
13	9±0.26f	11.6±0.31h
14	6.3±0.15h	8.9±0.28i
15	5.5±0.34i	7.9±0.41j
16	3±0.26k	5.3±0.21k

Means followed by different letters within each column of each density are significantly different ($P < 0.05$, Tukey's test)

Discussion

For the first time, under laboratory conditions, we analyzed the functional response and rates of parasitism and attack of *P. pistaciae* across its lifespan, as a major biological control agent for the CPP. The observed functional response was Type II, with distinct age-dependent trends in parasitism and attack rates. The research emphasizes the crucial role of the parasitoid, *P. pistaciae*, in diminishing the population of its host, the CPP, *A. pistaciae*, under controlled laboratory conditions. Throughout the first week of its life, the parasitoid showed highly efficient performance, marked by increased levels of parasitism and feeding. This study further underscores the notable influence of the age of the parasitoid and host-feeding behavior on the functional response exhibited by *P. pistaciae*. The findings of this research illustrate the significant role that handling time can play in the efficient performance of parasitoids. Functional response, as defined by Murdoch *et al.* (1978), traditionally quantifies a parasitoid's ability to control a pest population. This study consistently observed a functional response of the second type across all parasitoid ages, evidenced by the linear coefficient (P_1) taking negative values. This aligns with the findings of Asadi *et al.* (2012), and others who reported either a type II (Chong & Oetting, 2006, 2007; González-Hernández *et al.*, 2005; Huang *et al.*, 2012; Joodaki *et al.*, 2018; Qin *et al.*, 2023) or a type III functional response for hymenopteran parasitoids, particularly those in the Encyrtidae family (Jones *et al.*, 2003; Sagarra *et al.*, 2000). The scarcity of type III models within Encyrtidae functional response studies remains unclear, potentially due to unexplored factors or limitations in experimental designs.

Consequently, the type II model often dominates observations on parasitoids, especially under controlled laboratory conditions where space and time are restricted. Similar constraints might have influenced the type II response observed here. A type II functional response, characterized by a diminishing parasitism rate as host density increases, can disrupt the host-parasitoid equilibrium due to an inverse relationship between host mortality and density. This, however, can also contribute to stabilizing the dynamics of the host population (Murdoch & Oaten, 1975). Notably, the equation for Rogers' random attack effectively captured the age-independent rise in the count of hosts under attack (via parasitism and feeding) as host density increased. In the present investigation, *P. pistaciae* exhibited the highest rates of parasitism (31.44 nymphs per day) and attack (38.44 nymphs per day) at the age of five days, rates that are significantly higher than those of other encyrtids, such as *P. zdeneki* (Hymenoptera: Encyrtidae), which, as reported by Asadi *et al.* (2012), parasitized 15.1 and attacked 17.65 nymphs of *Euphyllura pakistanica* (Hemiptera: Psyllidae) per day. The impact of the parasitoid's age on the functional response can be elucidated by a comprehensive model, which suggests that both the immediate attack rate and the handling duration (of the parasitoid) are influenced by the age of the parasitoid, an aspect frequently neglected in numerous functional response investigations. This implies that older parasitoids are likely to devote more time to non-searching activities (such as resting). In contrast, younger parasitoids are anticipated to participate more in searching, egg-laying, and predatory behaviors.

The information was incorporate into the results to address this oversight. In the experiments, the highest rate of parasitism and attack occurred in the first week of the wasp's life after emergence. In this regard, the obtained results were consistent with the results of previous experiments obtained from three other species of parasitoid wasps named *Anagyrus ananatis*, *Clausenia josefi*, and *Psyllaephagus zdeneki*, which respectively had the highest percentage of parasitism on the sixth, fourth, and sixth days of the parasitoid's life (Asadi *et al.*, 2012; Berlinger, 1973; González-Hernández *et al.*, 2005). The handling time for hosts attacked by *P. pistaciae* is consistent with the results obtained for other species of Encyrtidae wasps which ranges from 0.62 to 1.26 hours. Specifically, the wasp *Anagyrus* sp. has a handling time ranging from 0.85 to 1.8 hours, while the wasp *P. zdeneki* has a handling time between 1.36 to 6.05 hours (Asadi *et al.*, 2012). Since parasitoid wasps are photophilic and their activity predominantly occurs during the light period, lasting 16 hours (Starý, 1970), the handling time should align with the insect's behavior (Chen *et al*., 2006).

The host feeding and fecundity rates align with the findings of Mehrnejad (2006), which examined the evolutionary process and survival of *P. pistaciae* at different ages and feeding on a specific number of fourth instar psyllid nymphs (at a density of 40 hosts). The maximum feeding occurred on the parasitoid's life on day six (26.2 per day). In line with Mehrnejad's findings, the daily number of eggs laid by parasitoids increased rapidly during the first week of their life, mirroring the feeding behavior observed. This rapid increase in egg-laying then gradually decreased with small fluctuations until death, suggesting a strong correlation between feeding and fecundity in the early stages of the parasitoid's life. These results are consistent with the findings of our experiments (Mehrnejad, 1998; Mehrnejad & Copland, 2006a). Host-feeding is a crucial behavioral attribute among synovigenic parasitoid species, serving as a primary method for protein acquisition necessary for the aim of egg production. This particular behavioral feature shown by parasitoids has primarily been ignored. Host-feeding behavior significantly influences critical life-history traits in parasitoids, including fertility and lifespan, ultimately impacting their suitability (Bernstein & Jervis, 2008; De Bach, 1943 Shi *et al*., 2009). Omitting the role of host-feeding behavior in parasitoids can lead to substantial misinterpretations of host-parasitoid population dynamics, considering that in addition to parasitism, numerous parasitoids eradicate a considerable number of hosts through feeding, in addition to parasitism (Kidd & Jervis, 1989). A parasitoid's lifespan can be divided into distinct functional components, encompassing food resource utilization, host searching, and parasitism-related activities. The time distribution among these activities presents a significant challenge in decision-making for adult parasitoids striving to achieve optimal fitness (Bernstein & Jervis, 2008).

This research highlights that host feeding leads to an increase in the immediate attack rate and a decrease in the overall handling time for this parasitoid. Host feeding by parasitoids can contribute to host mortality through direct feeding damage or indirect effects like venom injection and probing (Kidd & Jervis, 1989). In the context of biological control, *P. pistaciae* demonstrated a significant range of mortality across psyllid nymphal stages, likely attributable to a combination of host feeding and parasitism. Mehranjed (2006a) found that *P. pistaciae* parasitized all five psyllid instars but preferred the third and fourth instars, avoiding the fifth due to strong defenses and the first and second due to their small size. The results from the search rate assessments for *P. pistaciae* indicated a generally wider range in younger females as opposed to older ones. This implies that *P. pistaciae* has the capacity to consume and parasitize more CPP nymphs within the initial five days of their existence. The capability of *P. pistaciae* to find, feed on, and parasitize the CPP throughout its lifespan, coupled with an appropriate attack rate, suggests that this parasitoid could be a potent contender for a biological control program aimed at CPP in Iran. This is especially pertinent in the Kerman province, where both the psyllid and the parasitoid are prevalent in the majority of pistachio orchards from April to November.

The functional response of parasitoids is key to understanding their role in biological control, as it explains how parasitism rates change with host density, which is essential for predicting population dynamics and assessing their effectiveness in pest control (Fernández-arhex & Corley, 2003). Combining biological control with selective chemical treatments that are compatible with parasitoids can improve the overall management of *A. pistaciae* populations, leading to more effective pest control. Laboratory findings confirmed the potential of *P. pistaciae* as a biological control agent against CPP. While functional response studies in controlled settings may not fully reflect natural conditions, they offer valuable insights. However, the success of this parasitoid in pest management requires further research to understand factors influencing its functional response and to integrate it effectively into biological control programs targeting CPP in Iran. To ensure the conservation and effectiveness of *P. pistaciae*, future efforts should evaluate the impact of pesticides, identify selective, low-risk alternatives, and promote integrated pest management (IPM) strategies. Habitat management practices can also support its natural populations in pistachio orchards, enhancing its role in sustainable pest control.

Author's Contributions

Hamid Rahimzadeh Behzadi: Investigation, methodology, draft preparation, funding acquisition; **Mahdi Ziaaddini:** Visualization, conceptualization, methodology, supervision, project administration, final review and edit; **Mohammad Amin**

Jalali: Visualization, methodology, formal analysis, final review and edit, **Fateme Ranjbar:** Formal analysis, final review and edit,

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Data Availability Statement

The datasets used and analyzed during the current study are available from the corresponding author upon request.

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Ethics Approval

Insects were used in this study. All applicable international, national, and institutional guide lines for the care and use of animals were followed. This article does not contain any studies with human participants performed by any of the authors.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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ارزیابی توانایی زنبور *Psyllaephagus pistaciae* (Hymenoptera: Encyrtidae) در کنترل *Agonoscena pistaciae* (Hemiptera: Aphalaridae) با استفاده از واکنش تابعی وابسته به عمر

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چکیده: زنبور (Hymenoptera: Encyrtidae) *Psyllaephagus pistaciae* دشمن طبیعی غالب آفت پسیل معمولی پسته (Hemiptera: Aphalaridae) *Agonoscena pistaciae* می‌باشد و این آفت به عنوان آفت کلیدی درختان پسته منطقه رفسنجان که در تولید پسته ایران پیشرو می‌باشد، شناخته شده است. در این تحقیق نحوه تاثیر سن پارازیتوئید ماده در نوع واکنش تابعی دو رفتار تغذیه‌ای آفت یعنی میزبان‌خواری و پارازیتیسم در تراکم‌های مختلف پسیل پسته و بصورت روزانه مورد بررسی قرار گرفت. رگرسیون لجستیک نشان دهنده واکنش تابعی نوع دوم بوده که با افزایش نرخ حمله وابسته به تراکم پسیل مشخص گردید. این نوع واکنش تابعی بوضوح در تمام سنین زنبور پارازیتوئید مشاهده گردید. زنبور ماده در هفته اول عمر خود از قدرت جستجوگری بالایی برای هر دو رفتار تغذیه‌ای میزبان‌خواری و پارازیتیسم برخوردار بوده است. با این وجود افزایش سن ماده، منجر به افزایش زمان دستیابی پارازیتوئید در هر دو فعالیت میزبان‌خواری و پارازیتیسم می‌گردد. بیشترین قدرت جستجوگری برای میزبان‌های مورد حمله (مجموع دو رفتار تغذیه‌ای) در روز هفتم و حداقل زمان دستیابی در روز پنجم بدست آمد. بیشترین میزان پارازیتسیم در روز پنجم از زندگی زنبور پارازیتوئید مشاهده شد که نشان‌دهنده کارایی بالا در میزان پارازیتیسم و نرخ حمله در مراحل اولیه زندگی این پارازیتوئید، به‌ویژه در هفته اول بوده است که تراکم میزبان و سن پارازیتوئید بطور قابل توجهی براین دو ویژِگی تاثیرگذار نشان داده شده است.

کلمات کلیدی: کنترل بیولوژیک، پارازیتوئیدها، میزبان‌خواری، تراکم‌های میزبان، پارازیتیسم

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