



مقاله پژوهشی

ارزیابی پراسنجه‌های جمعیت زنبور (*Aphidius matricariae* (Hymenoptera: Braconidae) روی شته یولاف *Rhopalosiphum padi* (Hemiptera: Aphididae) در دمای ۲۰ درجه سلسیوس

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(دریافت: پذیرش:)

چکیده

شته یولاف (*Rhopalosiphum padi*) از آفات مهم غلات و ناقل ویروس کوتولگی زرد جو است. زنبور پارازیتوئید *Aphidius matricariae* به‌عنوان یکی از عوامل مؤثر مهار زیستی این آفت شناخته می‌شود، اما بهره‌برداری از آن نیازمند توسعه روش‌های بهینه پرورش انبوه است. این پژوهش با هدف بررسی ویژگی‌های زیستی و پراسنجه‌های جمعیتی *A. matricariae* روی *R. padi* در دمای 20 ± 0.5 درجه سلسیوس و تعیین نرخ برداشت برای بهینه‌سازی تولید انبوه این پارازیتوئید انجام شد. پراسنجه‌های جمعیتی و شاخص‌های نرخ برداشت پایدار *A. matricariae* بر اساس جداول زندگی سنی حاصل از داده‌های بقا و باروری تعیین گردید. نتایج نشان داد که دوره رشد مراحل نابالغ *A. matricariae* به طور متوسط $14/90$ روز و طول عمر ماده‌های بالغ $14/27$ روز بود. میانگین باروری زنبور، تعداد $163/75$ تخم به ازای هر ماده برآورد شد. نرخ خالص تولیدمثل (R_0) برابر با $161/4$ دختر به ازای هر ماده در هر نسل و نرخ ذاتی افزایش جمعیت (r_m) برابر با $0/3511$ در روز بود. زمان دو برابر شدن جمعیت $1/971$ روز محاسبه شد که بیانگر ظرفیت بالای رشد جمعیت این گونه است. تحلیل نرخ برداشت نشان داد که می‌توان بخش قابل توجهی از جمعیت را بدون به خطر انداختن پایداری کلنی برداشت کرد. این یافته‌ها بیانگر توان زیستی و جمعیتی مطلوب *A. matricariae* روی *R. padi* در دمای ۲۰ درجه سلسیوس است و اهمیت کاربرد نرخ برداشت را برای بهینه‌سازی تولید انبوه آن خاطر نشان می‌کند اما برای کاربرد نتایج در بهبود برنامه‌های رهاسازی تقویتی در مهار زیستی شته یولاف پژوهش بیشتری پیشنهاد می‌شود.

واژه‌های کلیدی: زنبور پارازیتوئید *Aphidius matricariae*، شته یولاف، جمعیت نگاری، پرورش انبوه، تحلیل نرخ برداشت



Research Article

Demographic Assessment of *Aphidius matricariae* (Hymenoptera: Braconidae) on *Rhopalosiphum padi* (Homoptera: Aphididae) at 20°CNARJES KARIMI¹, SHAHRAM SHAHROKHI KHANEGAH² , SHIMA RAHMANI³, YAGHOUB FATHIPOUR⁴

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Abstract

The bird cherry-oat aphid (*Rhopalosiphum padi*) is a major pest of cereals and a vector of barley yellow dwarf virus. The parasitoid wasp *Aphidius matricariae* is recognized as an effective biological control agent of this pest, but its utilization requires the development of optimal mass-rearing methods. This study investigated the biological characteristics and population parameters of *A. matricariae* on *R. padi* at 20 ± 0.5 °C and evaluated the harvest rate function for optimizing the mass production of this parasitoid. To assess the mass-production potential of *A. matricariae*, its population parameters and stable harvest rate indices were determined based on age-specific life tables derived from survival and fecundity data of the parasitoid. The results showed that the immature developmental period of *A. matricariae* averaged 14.90 days, and the longevity of adult females was 14.27 days. The mean lifetime fecundity was estimated at 163.75 eggs per female. The net reproductive rate (R_0) was 161.4 daughters per female per generation, and the intrinsic rate of increase (r_m) was 0.3511 per day. In addition, the population doubling time was 1.971 days. Harvest rate analysis showed that a portion of the population can be harvested without jeopardizing colony stability. These findings indicate the biotic potential of *A. matricariae* on *R. padi* at 20 ± 0.5 °C and suggest applying the harvest rate framework to optimize mass production for *A. matricariae*. Further information is required to apply the results in the biological control of the bird cherry-oat aphid using *A. matricariae*.

Keyword: *Aphidius matricariae*, *Rhopalosiphum padi*, Demography, Mass rearing, Harvest-rate analysis

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Introduction

Biological control is a key component of sustainable integrated pest management (IPM). It relies on natural enemies, including parasitoids, predators, and pathogens, to suppress pest populations. As a result, it generally reduces dependence on chemical insecticides and limits their adverse effects on non-target organisms and the environment (Eilenberg *et al.* 2001; Stenberg *et al.* 2017; Hajek & Eilenberg, 2018; Baker *et al.* 2020; Ferrer-Suay *et al.* 2025). Among agriculturally important pests, aphids are particularly important because of their high reproductive capacity, phloem-feeding habit, and ability to transmit plant viruses (Quisenberry & Ni, 2007). The bird cherry-oat aphid, *Rhopalosiphum padi* (L.) (Hemiptera: Aphididae), is an economically important pest of wheat, barley, and maize in many regions and can reduce crop growth and yield through phloem feeding and virus transmission. In particular, its role as an important vector of Barley Yellow Dwarf Virus (BYDV) increases its significance in cereal production systems (Perry *et al.* 2000; Savaris *et al.* 2013; Nancarrow *et al.* 2021; Leybourne, 2024). Consequently, the development of effective biological control strategies against *R. padi* is of considerable importance.

Parasitoid wasps are important natural enemies of aphids and play a significant role in their biological control. Within the Aphidiinae, *Aphidius matricariae* Haliday (Hymenoptera: Braconidae) is a solitary, endoparasitic, koinobiont, and oligophagous parasitoid that attacks a relatively broad range of aphid species (Starý, 1976; Giri *et al.* 1982; Hofsvang & Hågvar, 1986; Boivin *et al.* 2012). Its ability to parasitize agriculturally important aphids has resulted in considerable interest in its use as a biological control agent (Wick, 1992; Zamani *et al.* 2007). In Iran, *A. matricariae* is also an important component of the parasitoid complex associated with cereal aphids. Rakhshani *et al.* (2008) reported this species from several cereal aphids, including *R. padi*, during a survey conducted across 12 provinces of Iran. Previous studies have further demonstrated that the biological and demographic characteristics of *A. matricariae* can vary depending on the aphid host and associated rearing conditions (Zamani *et al.* 2007). These findings emphasize the importance of evaluating parasitoid performance within specific host systems rather than assuming that its biological characteristics are consistent across different hosts. The successful use of *A. matricariae* in augmentative biological control requires the continuous production of high-quality parasitoids. However, mass rearing of a parasitoid requires the simultaneous maintenance of the host plant, aphid host, and parasitoid, while maintaining the biological quality of the reared population (Parra, 2010; Sheppard *et al.* 2019; Leppla, 2023). Host plant and aphid species can influence parasitoid development, survival, reproduction, and demographic performance. For example, Jafari *et al.* (2020) demonstrated that wheat cultivar affected the developmental and demographic characteristics of *A. matricariae* in the wheat-*R. padi*-*A. matricariae* tritrophic system, whereas Rezaei *et al.* (2022) reported differences in

the biological and demographic traits of the parasitoid among different plant-aphid rearing systems. Temperature is another major factor affecting insect development, survival, longevity, and reproduction (Goh *et al.* 2001; Liu & Tsai, 2002; Zamani *et al.* 2002). Therefore, evaluating demographic performance at a defined, stable rearing temperature is important for characterizing the production potential of a parasitoid rearing system. In the present study, *A. matricariae* was evaluated at a constant temperature of 20 ± 0.5 °C. This temperature was selected because the fecundity of *R. padi* has been reported to be highest at 20 °C (Dean, 1974), the developmental biology of both *R. padi* and *A. matricariae* has been documented at this temperature (Agamy *et al.* 2003), and *A. matricariae* shows efficient development and reproduction at 20 °C, including high pupal survival exceeding 90% and a female-biased sex ratio (Zamani *et al.* 2007; Zepeda-Paulo *et al.* 2025), the highest intrinsic rate of increase among the temperatures tested, although not significantly different from those at 22 and 25 °C (Farsi *et al.* 2019), and a higher net reproductive rate than at 25 and 30 °C (Rashki *et al.* 2020). In addition, the relatively short developmental period at 20 °C (El-Heneidy *et al.* 2003; Zamani *et al.* 2007) is a desirable characteristic for mass-rearing systems.

In mass-rearing systems, however, production efficiency cannot be evaluated solely from the number of parasitoids produced. The timing and intensity of harvesting must also be considered because excessive or improperly timed removal of individuals may reduce the reproductive capacity and recovery of the parental population. Life-table analysis provides an integrated framework for evaluating age-specific survival, reproduction, population growth, and reproductive potential, and can therefore provide useful information for managing insect production systems (Carey *et al.* 1982; Chi, 1994; Chi *et al.* 2020; Hung *et al.* 2021). Demographic harvesting theory was originally developed to determine appropriate exploitation levels that allow populations to be harvested while maintaining their capacity for persistence and regeneration (Beddington & Taylor, 1973; Goodman, 1980). Application of this concept to laboratory insect production can provide estimates of harvesting age and sustainable harvesting rates while accounting for population growth and regenerative capacity. Despite the extensive use of life-table approaches for assessing parasitoid biology and mass-rearing performance, the application of a systematic harvesting-rate framework to aphid parasitoid production remains limited.

Therefore, the present study applies a life-table-based demographic harvesting-rate framework to evaluate the production potential of *A. matricariae* on *R. padi* at 20 ± 0.5 °C. The specific objectives were to (1) construct a life table for *A. matricariae* reared on *R. padi*; (2) estimate demographic parameters relevant to parasitoid production; (3) determine the appropriate timing and sustainable rate of parasitoid harvesting; and (4) evaluate the potential of the *A.*

matricariae–*R. padi* system for efficient mass production for augmentative biological control

Materials and methods

Collection and laboratory rearing of *A. matricariae*

A. matricariae populations were collected from wheat and barley fields in Varamin, Tehran Province, Iran, by sampling leaves containing mummified aphids. Each leaf was placed separately in a ventilated plastic container and transported to the laboratory. The containers were maintained under controlled conditions (20 ± 0.5 °C, $70 \pm 5\%$ relative humidity (RH), and a 16:8 h L:D) until parasitoid adults emerged. Newly emerged adults were collected with an aspirator and transferred to wheat plants infested with aphids to establish colonies. Species identification was performed using the identification keys of Starý (1976) and subsequently confirmed by a taxonomic specialist. Laboratory colonies of *A. matricariae* were established using *R. padi* reared on wheat of the ‘Mihan’ cultivar under the same environmental conditions. Wheat plants were used as the host plants for parasitoid rearing and subsequent experiments. To minimize the risk of hyperparasitoid contamination, only parasitoid adults that had naturally emerged from field-collected mummies were used to establish the laboratory colony; the field-collected mummies themselves were not directly introduced into the rearing colony. Newly emerged parasitoids were transferred to the rearing units using an aspirator. For colony maintenance, 1–2-day-old mated female *A. matricariae* were released onto wheat plants infested with second- and third-instar *R. padi* nymphs at an appropriate host-to-parasitoid ratio.

Determination of Immature Developmental Periods

To determine the immature developmental periods, newly emerged adult *A. matricariae* parasitoids less than 24 h old, consisting of one female and one male, were selected. Adult parasitoids were provided with a 10% honey–water solution as a carbohydrate source. Using an aspirator, the parasitoids were transferred to two-leaf-stage wheat seedlings of the ‘Mihan’ cultivar infested with approximately 50 second- and third-instar *R. padi* nymphs. Thus, the parasitoid-to-host ratio was 2:50 (one female and one male per 50 aphid nymphs). Each experimental unit consisted of a plastic container measuring 6 cm in diameter and 8 cm in height. Parasitoids were allowed to parasitize the hosts for 24 h, after which adults were removed from the containers using an aspirator. Exposed aphids, together with their respective wheat seedlings, were maintained individually under controlled conditions at 20 ± 0.5 °C, $70 \pm 5\%$ RH, and a 16:8 h L:D photoperiod. Containers were examined daily, and the time of mummy formation was recorded. Subsequently, 100 mummies were randomly selected, and each was placed individually in a glass vial and maintained under the same environmental conditions until adult emergence. The date of adult emergence and sex were recorded. Accordingly, developmental periods

were determined as the duration from oviposition to mummy formation, from mummy formation to adult emergence, and the total immature developmental period. Mummy-stage mortality was calculated as the percentage of mummies that failed to produce an adult parasitoid.

Adult survival and fecundity

To evaluate adult longevity and reproductive performance, 25 newly emerged *A. matricariae* females less than 24 h old were used. Each female was transferred individually to a polyethylene container measuring 6 cm in diameter and 8 cm in height using an aspirator. Each container contained approximately 50 second- and third-instar *R. padi* nymphs on a two-leaf-stage wheat seedling of the ‘Mihan’ cultivar, together with one adult male parasitoid. Thus, during each 24-h exposure period, each female had access to approximately 50 fresh host nymphs. Adult parasitoids were provided with a 10% honey–water solution as a carbohydrate source. The parasitoids were maintained under controlled conditions at 20 ± 0.5 °C, $70 \pm 5\%$ RH, and a 16:8 h L:D photoperiod. After 24 h, each female was removed using an aspirator and transferred to a new container containing approximately 50 fresh second- and third-instar *R. padi* nymphs and a fresh wheat seedling. This procedure was repeated at 24-h intervals until the death of each female. The aphids exposed to each female parasitoid, together with their respective wheat seedlings, were maintained separately after each 24-h exposure period and examined daily for mummy formation. The number of mummies produced by each female was recorded, and the mummies were maintained under the same environmental conditions until adult emergence. Emerged adults were counted and sexed to determine offspring production and sex ratio. A 10% honey–water solution was provided as a food source for adult parasitoids throughout the experiments.

Life-table and demographic analysis

Age-specific survival (l_x) and age-specific fecundity (m_x) schedules were constructed from the daily records. The net maternity schedule ($l_x m_x$) was calculated from these data and used to estimate demographic parameters. Life-table parameters were calculated according to Carey (1993), including the net reproductive rate (R_0), intrinsic rate of increase (r_m), finite rate of increase (λ), mean generation time (T), and doubling time (DT). These parameters were used to describe the population growth potential of *A. matricariae* under laboratory conditions at 20 ± 0.5 °C.

Application of Demographic Harvesting Theory to Mass Rearing

Demographic harvesting analysis was performed to estimate sustainable harvest rates under stable population conditions. Mass rearing can be modeled as a demographic harvesting system in which specific stages are harvested while the colony remains stable. This study followed the framework of Carey and Vargas (1985) and Carey (1993). Harvesting is treated as an additional source of mortality. The analysis was based on age-specific survivorship (l_x) and age-specific fecundity (m_x).

Harvest-rate and discard-age calculations

For the harvest-rate and discard-age calculations, male and female individuals were assumed to have similar growth, development, and survival rates. A theoretical 1:1 sex ratio was adopted in the demographic model to simplify estimation of sustainable harvest rates. Therefore, l_x represents the survival of female insects up to age x , and m_x represents the rate of female offspring production by females of age x . The net reproductive rate of daughters produced by each female from the first reproductive age (α) until the discard age (δ) is expressed as:

$$\phi_x = l_x m_x \quad (1)$$

The sum of ϕ_x overall reproductive age classes define the net reproductive rate (R_0), representing the expected number of daughters produced by a female during her lifetime and the factor by which the population increases from one generation to the next.

$$R_0 = \sum_{x=\alpha}^{\delta} \phi_x \quad (2)$$

where α and δ represent the ages of first and last reproduction, respectively. The net reproductive rate (R_0) indicates the rate of population growth from one generation to the next. The finite rate of increase (λ) is the rate of population growth per unit time and is a measure of the increase of the population in a unit time, and is related to the life-table schedules via Carey and Vargas (1985).

$$1 = \sum_{x=\alpha}^{\delta} \lambda^{-x} \phi_x \quad (3)$$

This equation, known as the renewal equation, is a β th-order polynomial in λ . It has one positive real root, called the **finite rate of increase** of the population.

The stable age distribution describes the proportion of individuals in each age class within the long-term population. It is calculated from:

$$c_x = \frac{\lambda^{-x} l_x}{\sum_{x=\varepsilon}^{\omega} \lambda^{-x} l_x} \quad (4)$$

where c_x is the fraction of the population aged x to $x + 1$, and ω is the maximum possible lifespan. Note that when $\lambda = 1$ (a stationary population), the term λ^{-x} in both the numerator and denominator equals 1 and therefore drops out.

The goal of a mass-rearing program is to maintain a population at a constant size while producing eggs. At age θ , a fraction h of the offspring is harvested, leaving a fraction $(1-h)$ to maintain the colony. To keep the population size constant, the harvest rate must result in zero population growth. Therefore, the value of h is determined by solving the following equation:

$$\left(1 = (1-h) \sum_{x=\theta}^{\delta} \phi_x \right) \quad (5a)$$

$$\left(h = 1 - \left(\sum_{x=\theta}^{\delta} \phi_x \right)^{-1} \right) \quad (5b)$$

where θ is the discard age. In this case, age θ becomes the artificially imposed last age of reproduction.

The corresponding stable age distribution for the population within the rearing facility is given by:

$$c_x = \begin{cases} \frac{l_x}{s} & \text{For } x < \theta \\ \frac{l_x (1-h)}{s} & \text{For } x \geq \theta \end{cases} \quad (6)$$

where

$$s = \sum_{x=0}^{\theta-1} l_x + (1-h) \sum_{x=\theta}^{\delta} l_x \quad (7)$$

If C_0 represents the proportion of the target life stage at age θ in the post-harvest colony, then the following expression applies:

$$\rho = \frac{2h}{1-h} \times \frac{c_\theta}{\sum_{x=\varepsilon}^{\delta} c_x} \quad (8)$$

It gives the daily yield of the target stage, ρ , per female, where ε denotes the age at eclosion. The factor of 2 in Equation 8 accounts for the production of males, assuming a 1:1 sex ratio.

Because the c_x values are defined in terms of the l_x values, and h is defined in terms of ϕ_x , ρ can also be expressed as:

$$\rho = \frac{2l_{\theta}[(\sum_{x=\alpha}^{\delta} \phi_x) - 1]}{\sum_{x=\epsilon}^{\delta} l_x} \quad (9) \quad \text{where} \quad l_{\theta}$$

represents survival to the target stage in the unharvested population. This form is particularly useful because the per-female productivity of the target stage can be calculated directly from the survival schedules and the cumulative net maternity schedule

Statistical analysis

Developmental time, adult longevity, lifespan, oviposition period, and fecundity of *A. matricariae* were summarized as mean $\pm$ standard error (SE). Descriptive statistics, including minimum and maximum values, were calculated for all biological parameters. Age-specific survival (l_x) and age-specific fecundity (m_x) schedules were used to construct life tables and estimate demographic parameters. The net reproductive rate (R_0), intrinsic rate of increase (r_m), finite rate of increase (λ), mean generation time (T), doubling time (DT), gross fecundity rate, gross fertility rate, net fecundity rate, and net fertility rate were calculated according to the procedures described by Carey (1993). Demographic harvesting parameters, including host harvest rate (h_h), female parasitoid harvest rate (h_f), daily host production rate (ρ_h), daily parasitoid production rate (ρ_f), and host-to-parasitoid ratio, were estimated following the demographic harvesting approach described by Carey and Vargas (1985). The primary sex ratio was calculated as the proportion of female and male offspring among the emerged adults. All data are presented as mean $\pm$ SE

Results

Development, survival, and demographic characteristics of *A. matricariae*

The developmental and reproductive characteristics of *A. matricariae* reared on *R. padi* at 20 ± 0.5 °C are presented in Tables 1–5. Immature development from oviposition to adult emergence required approximately 14.896 ± 0.104 days. Mean longevity was 14.266 ± 0.133 days for females and 10.101 ± 0.185 days for males. Total lifespan averaged 29.095 ± 0.165

days for females and 25.118 ± 0.206 days for males. The total lifespan (combined data for both sexes) was 27.664 ± 0.197 days (Table 1). Female parasitoids exhibited no preoviposition period (0 days). The oviposition period lasted 11.781 ± 0.251 days, followed by a post oviposition period of 2.524 ± 0.223 days. Mean lifetime fecundity was 163.752 ± 5.758 eggs per female, with a range of 57 to 286 eggs (Table 2). The age-specific survival (l_x) and age-specific fecundity (m_x) schedules are illustrated in Figure 1. The gross fecundity rate was 270.30, and the gross fertility rate was 221.64, giving a gross hatch rate of 0.82. The net fecundity rate was 254.80, and the net fertility rate was 208.93. The mean age of gross fecundity and gross fertility was 15.94 days, while the mean age of net fecundity and net fertility was 15.57 days. The mean age at hatch was 21.50 days. Females produced an average of 12.29 eggs and 10.07 fertile eggs per day. The daily reproductive rate was 16.86 eggs per female per day and 13.82 fertile eggs per female per day (Table 3). The net reproductive rate (R_0) was 161.4 female offspring per female per generation. The intrinsic rate of increase (r_m) was 0.3511 day^{-1} , and the finite rate of increase (λ) was 1.421. The mean generation time (T) was 14.48 days, and the population doubling time (DT) was 1.97 days (Table 4). Demographic harvesting analysis was performed to estimate sustainable harvest rates under stable population conditions. Parameters obtained from the demographic harvesting model are presented in Table 5. The estimated harvest rate for female parasitoids (h_f) was 0.993, whereas the host harvest rate (h_h) was 0.981. The daily host production rate (ρ_h) was 4.568 female offspring per female per day, and the daily female parasitoid production rate (ρ_f) was 13.603 female eggs per female per day. The estimated host-to-parasitoid ratio was 5.30:1. The demographic harvesting parameters are summarized graphically in Figure 2. These estimates indicate that only a small proportion of the host and parasitoid populations is theoretically required for colony maintenance. Under equilibrium conditions, approximately 98.1% of the host population and 99.3% of the female parasitoid population could be harvested while maintaining a stable population structure. The parasitoid production rate (ρ_f = 13.603 female eggs per female per day) was approximately three times higher than the host production rate (ρ_h = 4.568 female offspring per female per day). The primary sex ratio of the emerged progeny was female-biased. The female proportion was 0.5625, and the male proportion was 0.4375, resulting in a female-to-male ratio of approximately 1:0.78.

جدول ۱. دوره رشدی، طول عمر افراد بالغ و طول عمر کل زنبور *Aphidius matricariae* روی *Rhopalosiphum padi* در دمای ۵/۰ ± ۲۰ درجه سلسیوس، رطوبت نسبی ۵ ± ۷۰ درصد و دوره نوری ۱۶ ساعت روشنایی: ۸ ساعت تاریکی

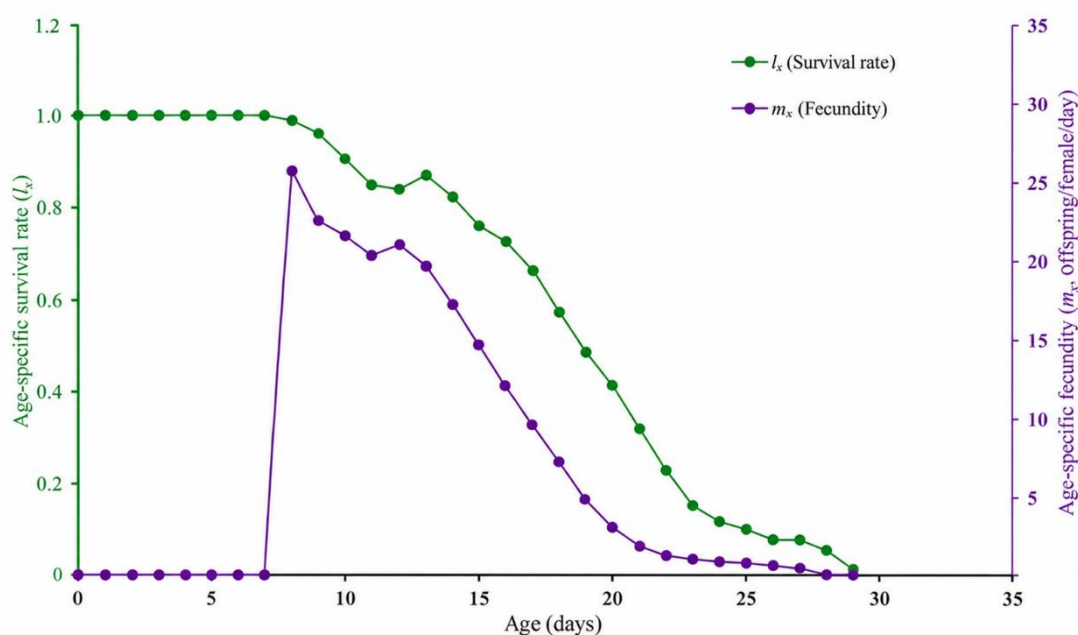
Table 1. Developmental time, adult longevity, and total lifespan of *Aphidius matricariae* on *Rhopalosiphum padi* at 20 ± 0.5 °C, 70 ± 5% RH, and 16L:8D.

Parameter (day)	N	Mean ± SE (days)	Range (min–max)
Immature development (egg to adult)	164	14.896 ± 0.104	11–18
Developmental time of Female	105	14.828 ± 0.130	11–18
Developmental time of Male	59	15.016 ± 0.175	11–17
Female longevity	105	14.266 ± 0.133	10–17
Male longevity	59	10.101 ± 0.185	7–17
Female lifespan (oviposition to death)	105	29.095 ± 0.165	25–33
Male lifespan	59	25.118 ± 0.206	20–28
Total lifespan (both sexes)	164	27.664 ± 0.197	20–33

جدول ۲. پراسنجه‌های تخم‌گذاری و باروری زنبورهای ماده *Aphidius matricariae* روی *Rhopalosiphum padi* در دمای ۵/۰ ± ۲۰ درجه سلسیوس، رطوبت نسبی ۵ ± ۷۰ درصد و دوره نوری ۱۶ ساعت روشنایی: ۸ ساعت تاریکی (تعداد نمونه = ۱۰۵)

Table 2. Oviposition parameters and fecundity of *Aphidius matricariae* females on *Rhopalosiphum padi* at 20 ± 0.5 °C, 70 ± 5% RH, and 16L:8D (N = 105).

Parameter	Mean ± SE	Range (min–max)
Preoviposition period (days)	0	–
Oviposition period (days)	11.781 ± 0.251	7–17
Postoviposition period (days)	2.524 ± 0.223	0–7
Lifetime fecundity (total eggs/female)	163.752 ± 5.758	57–286



شکل ۱. نرخ بقای ویژه سن (l_x) و باروری ویژه سن (m_x) زنبور پارازیتوئید *Aphidius matricariae* روی شته یولاف *Rhopalosiphum padi* در دمای 20 ± 0.5 درجه سلسیوس، رطوبت نسبی 70 ± 5 درصد و دوره نوری ۱۶ ساعت روشنایی: ۸ ساعت تاریکی

Figure 1. Age-specific survival rate (l_x) and Age-specific fecundity (m_x) of *Aphidius matricariae* on *Rhopalosiphum padi* at 20 ± 0.5 °C, $70 \pm 5\%$ RH, and 16L:8D.

جدول ۳. پراسنجه‌های تولیدمثلی *Aphidius matricariae* روی *Rhopalosiphum padi* در دمای 20 ± 0.5 درجه سلسیوس، رطوبت نسبی 70 ± 5 درصد و دوره نوری ۱۶ ساعت روشنایی: ۸ ساعت تاریکی

Table 3. Reproductive parameters of *Aphidius matricariae* on *Rhopalosiphum padi* at 20 ± 0.5 °C, $60 \pm 5\%$ RH, and a 16L:8D

Parameter		Value	Unit
Lifetime reproductive	Gross fecundity	270.30	eggs
	Gross fertility	221.64	Fertile eggs
	Gross hatch	0.82	-
	Net fecundity	254.80	eggs
	Net fertility	208.93	Fertile eggs
Mean age of reproduction	Mean age at gross fecundity	15.94	days
	Mean age gross fertility	15.94	days
	Mean age net fecundity	15.57	days
	Mean age net fertility	15.57	days
	Mean age hatch	21.50	days
Daily reproductive rate	Mean eggs per day	12.286	eggs/day
	eggs/female/day	16.857	eggs/parasitoid-day
	Mean fertile eggs per day	10.075	eggs/day
	Fertile eggs/female/day	13.823	eggs/parasitoid-day

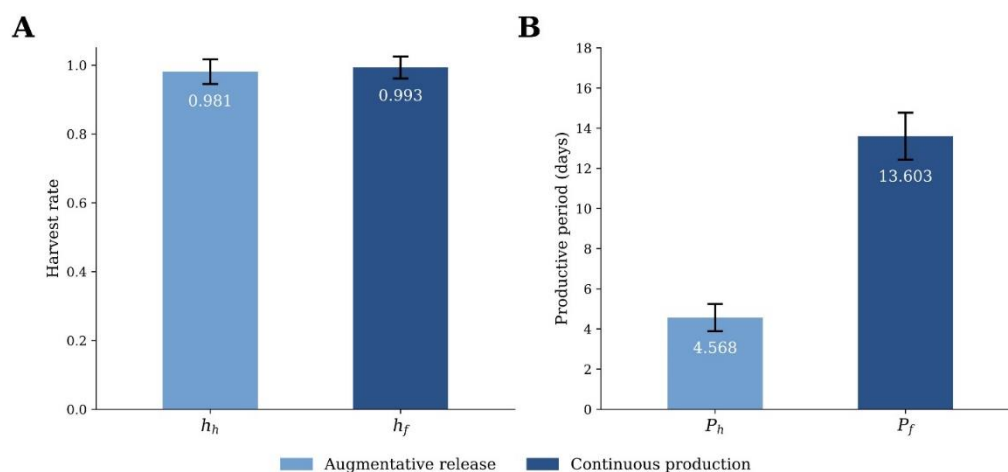
جدول ۴. پراسنجه‌های رشد جمعیت *Aphidius matricariae* بر اساس جداول نرخ بقای ویژه سن (l_x) و باروری ویژه سن (m_x)

Table 4. Population growth parameters of *Aphidius matricariae* based on Age-specific survival (l_x) and Age-specific fecundity (m_x) schedules.

Parameter	Value	
Net reproductive rate (R_0) (female offspring per female)	161.4	
Intrinsic rate of increase (r_m) (day ⁻¹)	0.3511	
Finite rate of increase (λ) (day ⁻¹)	1.421	
Mean generation time (T) (day)	14.48	
Doubling time eggs/day (DT) (day)	1.97	جدول ۵. پراسنجه‌های
مدل برداشت برای		
<i>Aphidius. matricariae</i> روی <i>Rhopalosiphum. padi</i> در دمای 20 ± 0.5 درجه سلسیوس، رطوبت نسبی 70 ± 5 درصد و دوره نوری ۱۶ ساعت روشنایی: ۸ ساعت تاریکی		

Table 5. Harvesting model parameters for *Aphidius matricariae* on *Rhopalosiphum padi* at $20 \pm 0.5^\circ\text{C}$, $70 \pm 5\%$ RH, and 16L:8D

Parameter	Symbol	Value	Unit
Host harvest rate	h_h	0.981	-
Female parasitoid harvest rate	h_f	0.993 (99.3%)	-
Daily host production rate	ρ_h	4.568	female eggs/female/day
Daily female parasitoid production rate	ρ_f	13.603	female eggs/female/day
Host-to-parasitoid ratio	—	5.30	hosts/parasitoid female



شکل ۲. تحلیل نرخ برداشت *Aphidius matricariae* در دمای 20 ± 0.5 درجه سلسیوس. h_h نرخ برداشت برای رهاسازی اشباعی؛ h_f ، نرخ برداشت برای تولید مداوم؛ P_h ، دوره بهره‌وری برای رهاسازی اشباعی (روز)؛ و P_f ، دوره بهره‌وری برای تولید مداوم (روز). خطای استاندارد (SE) در شکل مشخص هستند.

Figure 2. Harvest rate analysis of *Aphidius matricariae* at 20 ± 0.5 °C. h_h , harvest rate for augmentative release; h_f , harvest rate for continuous production; P_h , productive period for augmentative release (days); and P_f , productive period for continuous production (days). Error bars represent SE.

Discussion

Demographic and Population Growth Parameters

In the present study, the age-specific survival rate (l_x) of *A. matricariae* at 20 ± 0.5 °C was high during the early stages of life and decreased with increasing age, whereas the age-specific fecundity rate (m_x) reached its maximum at the beginning of the reproductive period and subsequently declined. This pattern indicates that a major proportion of survival and reproduction was concentrated during the early stages of life and could contribute to rapid population increase. A similar pattern has been reported for *A. matricariae* under different temperature and host conditions (Rashki *et al.* 2020; Farsi *et al.* 2019). The observed differences among studies may be attributed to rearing conditions, temperature, and host characteristics.

The net reproductive rate (R_0) in the present study was 161.43 female offspring per female per generation, indicating a high potential for population increase of *A. matricariae* on *R. padi*. This value was higher than those reported by Rashki *et al.* (2020) for *Schizaphis graminum* and by Zamani *et al.* (2012) for *Aphis gossypii*, and differed from the value reported by Jafari *et al.* (2020) at 25°C on *R. padi*. Reproductive performance of *A. matricariae* on other aphid hosts has also been documented by Tahriri Adabi *et al.* (2010) on *Aphis fabae*. These differences are likely attributable to interactions among host quality, host plant, temperature, and rearing

conditions. In particular, Rezaei *et al.* (2022) showed that plant-aphid combinations can affect the biological performance and demographic parameters of *A. matricariae*. Therefore, the high R_0 observed in the present study indicates the suitability of the wheat-*R. padi* system for population increase of *A. matricariae* under the tested conditions.

To further assess the biological-control potential of *A. matricariae*, its demographic performance can also be evaluated in relation to that of its host, *R. padi*. Jafari *et al.* (2020) reported that at 25 °C, the intrinsic rate of increase of *R. padi* was 0.426 day^{-1} on the susceptible wheat cultivar Pishgam, compared with 0.337 day^{-1} for *A. matricariae*, whereas on the resistant cultivar Shahriar, the r_m of *R. padi* decreased to 0.183 day^{-1} compared with 0.330 day^{-1} for the parasitoid. In the present study, at 20 °C on wheat cultivar Mihan, the r_m of *A. matricariae* (0.351 day^{-1}) was slightly higher than that of *R. padi* (0.326 day^{-1}), while the parasitoid had a substantially higher R_0 (161.4 vs. 47.03). These results suggest that the relative demographic performance of the parasitoid and host may influence the potential of *A. matricariae* to suppress *R. padi*. When the host population increases faster than the parasitoid, as observed on the susceptible Pishgam cultivar, the capacity of the parasitoid to suppress host population growth may be limited; conversely,

when parasitoid population growth exceeds that of the host, as observed in the present study and on the resistant Shahriar cultivar, more favorable conditions for host suppression may occur. However, these comparisons should be interpreted cautiously because temperature, wheat cultivar, and experimental conditions differed among studies. The finite rate of increase (λ) in the present study was **1.421 per day**, indicating a rapid population increase under the experimental conditions.

This value was within the range reported for *A. matricariae* in previous studies (Shahrokhi-Khanqah et al. 2004; Tahriri Adabi et al. 2010; Jafari et al., 2020; Rashki et al. 2020) and was consistent with the value reported by Farsi et al. (2019) at 20°C. The suitability of these conditions for population growth is also consistent with the report by Zamani et al. (2012) of better reproductive performance of *A. matricariae* at 20°C. In addition, differences in parasitoid performance among different plant-aphid combinations (Rezaei et al. 2022; Korkmaz and Karacaoğlu, 2025; Alvarez-Baca et al. 2020) indicate that λ should also be interpreted in relation to host quality and the complete plant-aphid-parasitoid system. Therefore, the relatively high λ observed in the present study, together with the high R_0 , indicates favorable conditions for population increase of *A. matricariae* in the studied system. The mean generation time (T) and population doubling time (DT) in the present study were 14.48 and 1.97 days, respectively, indicating a short generation interval and a high rate of population increase. These parameters are influenced by temperature and rearing conditions, and differences among studies have been reported for *A. matricariae* (Pourtaghi et al. 2016; Hajrahmatollahi et al. 2013; Farsi et al. 2019; Shahrokhi-Khanqah et al. 2004; Tahriri Adabi et al. 2010; Jafari et al. 2020). In addition, shorter developmental times at higher temperatures have been reported in studies by Agamy et al. (2003), Zamani et al. (2007), and Zepeda-Paulo et al. (2025), highlighting the importance of temperature in determining the rate of growth and generation turnover. Overall, the combination of a high R_0 , high λ , short T , and short DT observed in the present study indicates the suitable demographic capacity of *A. matricariae* on *R. padi* and the potential of this system for mass rearing under the tested conditions.

Demographic Harvest Analysis

In the present study, demographic harvest analysis showed that the host harvest rate (h_h) and female parasitoid harvest rate (h_f) were 0.981 and 0.993, respectively. These values indicate that, under demographic equilibrium conditions, a large proportion of the individuals produced can be harvested, while a portion of the population remains to maintain and renew the colony.

A demographic harvesting framework has also been applied to parasitoid mass rearing by Carey et al. (1988), who estimated female parasitoid harvest rates of 0.925–0.960 for *Biosteres tryoni* at different discard ages. The female parasitoid harvest rate obtained in the present study (0.993) was higher than these values. However, this comparison should be interpreted cautiously because the two parasitoid species differ in their biology, host species, rearing conditions, and discard ages. Nevertheless, the application of the same demographic harvesting concept to a braconid parasitoid provides a useful reference for interpreting the high female parasitoid harvest rate obtained for *A. matricariae*. The female production rate (ρ_f) in the present study was 13.603 female offspring per female per day, which was very close to the value reported by Amir-Maafi (2003) for *T. grandis* (13.2 female offspring per female per day). This similarity, despite differences in parasitoid and host species, indicates a high capacity of both systems for producing female offspring. However, differences in parasitoid biology, host quality and age, and rearing conditions may affect the production rate.

The host-to-parasitoid ratio and host characteristics are also important factors affecting rearing efficiency. Previous studies have shown that the host-to-parasitoid ratio and host characteristics can affect host acceptance, parasitization rate, and offspring characteristics (Jubb & Watson, 1971; Powell & Shepard, 1982; Navasero & Oatman, 1989). In addition, Amir-Maafi and Parker (2011) showed that adjusting the host-to-parasitoid ratio and selecting the appropriate host age are important for achieving an efficient rearing method in *T. grandis*. Therefore, the host-parasitoid ratio obtained in the present study can be used to determine the amount of host required to maintain the *A. matricariae* population and to plan production. The reproductive pattern throughout the parasitoid's lifespan may also be important in determining the appropriate harvest time. Amir-Maafi and Parker (2011) reported that the highest reproduction in *T. grandis* occurred during the early days following adult emergence and attributed this pattern partly to ovarian maturation at emergence. Therefore, considering the age-specific reproductive pattern observed in the present study, the timing of harvesting should be coordinated with the reproductive period of the parasitoid so that a substantial proportion of the production can be harvested while sufficient individuals are retained for colony continuity.

Overall, the high harvest rates (h_h and h_f) and female production rate (ρ_f) in the present study indicate that *A. matricariae* on *R. padi* has suitable capacity for production and harvesting under rearing conditions. However, these rates are theoretical values derived from the population structure under laboratory conditions and the assumption of demographic equilibrium, and the stability of this pattern across successive generations and under actual rearing conditions should be evaluated to determine the practical harvest level at the mass-rearing scale.

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