Comparative analysis of the demographic parameters of seven spotted ladybird beetle (Coleoptera: Coccinellidae) reared on various host aphid species

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ABSTRACT

Background. The demographic parameters of the predacious seven spotted ladybird beetle *Coccinella septempunctata* Linnaeus (Coleoptera: Coccinellidae) reared on the following four host aphid species were compared: *Rhopalosiphum padi* Linnaeus (Hemiptera: Aphididae), *Rhopalosiphum maidis* Fitch (Hemiptera: Aphididae), *Sitobion avenae* Fabricius (Hemiptera: Aphididae), and *Schizaphis graminum* Rondani (Hemiptera: Aphididae).
Methods. The developmental period, fecundity, adult preoviposition period, total preoviposition period and population parameters were evaluated based on the two-sex age-stage life table. The duration of the developmental stages and the population parameters were calculated with the TWOSEX-MSChart program, whereas population size was projected based on the two-sex age-stage life table data with the TIMING-MSChart program.
Results. The intrinsic rate of increase (r) was the highest in the *R. padi* predators (0.1946 per day), followed by the *S. graminum* (0.1435 per day), *S. avenae* (0.1400 per day), and *R. maidis* (0.1180 per day) predators. The differences in the net reproductive rate (R_0) and the finite rate of increase (λ) when *C. septempunctata* was reared on the four aphid species were consistent with the r values. This trend was reversed for the mean generation time (T), which ranged from 29.02 days for the lady beetles reared on *R. padi* to 39.75 days for the lady beetles reared on *R. maidis*. Interestingly, *R. padi* was the most suitable host, while the congeneric *R. maidis* was the least suitable. The results of this study may be useful for future investigations regarding the ecological effects of predatory species and the mass-production of *C. septempunctata* in the laboratory for an augmentative release of an aphid predator.

INTRODUCTION

The family *Coccinellidae* comprises of more than 6,000 species (*Marin et al., 2010*) of ladybirds and includes the predacious beetles of economically important insect pests such as aphids, thrips, mites and whiteflies (*Gupta et al., 2012*; *Hodek & Honek, 1996*). One of the potential predacious ladybird, *Coccinella septempunctata* Linnaeus (Coleoptera: Coccinellidae), originally native to Palearctic region but now been prevalent in most parts of the world has been exploited as biocontrol agent in various control programs (*Honek & Martinkova, 2005*; *Krafsur, Obrycki & Harwood, 2005*) due to its feeding aggressiveness as well as high biotic potential and voracity (*Shannag & Obeidat, 2008*). Adults as well as grubs feed voraciously on immature and adult aphids and can consume from 40–173 aphids in a single day, thereby suppressing pest populations effectively (*Akram, Akbar & Mehmood, 1996*; *Sarwar & Saqib, 2010*; *Suhail et al., 1999*). It has been recognized globally and can prey on various aphid species, including *Macrosiphum rosae* Linnaeus (Hemiptera: Aphididae), *Myzus persicae* Sulzer (Hemiptera: Aphididae), *Schizaphis graminum* Rondani (Hemiptera: Aphididae), and *Lipaphis erysimi* Kaltenbach (Hemiptera: Aphididae) (*Rauf et al., 2013*, *Omkar & Pervez, 2002*).

C. occinella septempunctata developmental parameters are greatly influenced by the available prey species (*Hauge, Nielsen & Toft, 1998*; *Lakhanpal & Raj, 1998*; *Omkar, Srivastava & James, 1997*). When food is scarce, *C. septempunctata* continually seeks and consumes diverse food types, including fungal spores, thrips, whiteflies, citrus psyllid nymphs, hawthorn mealybugs, and Colorado potato beetles (*Cranshaw et al., 2000*; *Divender et al., 2000*; *Gusev et al., 1983*; *Kumar & Gupta, 2006*; *Triltsch, 1999*; *Zhang, Lü & Wan, 2007*). However, the ability of *C. septempunctata* to lay eggs depends mainly on the availability of specific aphid species (*Kalushkov & Hodek, 2004*). Aphids feeding on economically important plants, such as wheat, brassica, and rose, may represent appropriate food sources for mass-reared *C. septempunctata*. Prey abundance influences the female fecundity rate and clutch size (*Dixon & Guo, 1993*) and significantly affects aphid consumption by all larval instars. For example, the consumption of *L. erysimi* by *C. septempunctata* larvae significantly increases with increasing aphid density (*Solangi et al., 2007*).

A thorough understanding of pest ecology is crucial for developing a rigid, integrated pest management program (*Huang & Chi, 2012*). Characterizing the population ecology and bionomics requires a considerable amount of quantitative data (e.g., life table statistics of the target species). The importance of these data in conventional control programs, and as precursors to successful pest management, has been repeatedly emphasized (*Ali & Rizvi, 2007*; *Arshad & Parez, 2007*; *Conti et al., 2010*; *Ramalho et al., 2015*). Life tables play a vital role in population ecology studies because they provide broad information regarding basic population parameters such as development, survivorship, and reproduction. Additionally, life tables reveal the developmental parameters of two species in a predator–prey relationship, enabling the mass-rearing of the predator in the laboratory (*Chi, 1988*; *Chi & Yang, 2003*). Even if mass-rearing is difficult, it adds useful basal data for ecological

studies of the species, leading to potential field control in the future. Conventional age-specific life tables (*Birch, 1948*) consider only the female population and cannot differentiate between the developmental stages. Because the predation rate varies with the stage (i.e., the eggs and pupae of lady beetles are non-predacious and larger larvae consume more prey per unit time than smaller larvae), the female-only life table is unsuitable for analyzing predation rates. Moreover, because male lady beetles can also kill prey, ignoring the male population will underestimate the predation capacity of the predators (*Chi & Su, 2006*; *Khanamani, Fathipour & Hajiqanbar, 2013*). To address these flaws, *Chi & Liu (1985)* and *Chi (1988)* proposed the age-stage two-sex life table theory and developed corresponding methods for estimating the life history parameters.

Researchers previously investigated the possible effects of aphids on various aspects of *C. septempunctata* (*Blackman, 1967*; *Kawauchi, 1985*; *Obrycki & Orr, 1990*). In a recently published study, authors demonstrated the life table parameters of *C. septempunctata* against three aphid species, *Aphis craccivora* (Koch) (Hemiptera: Aphididae), *L. erysimi*, and *M. persicae* and concluded that *M. persicae* is the most suitable prey for this predatory beetle (*Farooq et al., 2018*). The current study is the continuation of previous work. Here, we quantified the comparative fitness of four aphid species (*Rhopalosiphum padi* Linnaeus (Hemiptera: Aphididae), *Rhopalosiphum maidis* Fitch (Hemiptera: Aphididae), *Sitobion avenae* Fabricius (Hemiptera: Aphididae), and *Schizaphis graminum* Rondani (Hemiptera: Aphididae)) as hosts of *C. septempunctata*. Additionally, we investigated the changes in the juveniles and the reproduction of the adults in response to each prey species. The survival, reproduction, and developmental parameters of *C. septempunctata* that fed on the different host species under laboratory conditions were elaborated in an age-stage two-sex life table. This information will clarify the feasibility of the mass-production of *C. septempunctata* as a possible biocontrol agent for pest management.

MATERIALS AND METHODS

Aphid cultures

Coccinella septempunctata was reared on *R. padi*, *R. maidis*, *S. avenae*, and *S. graminum*. To maintain enough aphid culture, aphids in the field were collected from research orchards of Ayub Agricultural Research Institute, Faisalabad, Pakistan (31°23′15.761″N; 73°2′59.772″E) in plastic jars and shifted to plastic cages in the laboratory for mass culturing where they were fed on fresh leaves of *Triticum aestivum*. To obtain cohorts of target larval instars, winged females were separated from the culture and allowed to mate with males in Petri dishes (90 mm ×10 mm) covered with muslin cloth. The neonates hatched were then shifted with the help of small camel hair brush to separate cages having fresh wheat leaves (*Gupta et al., 2012*). The temperature and relative humidity of the cultures were maintained at 24 ± 1 °C and 70 ± 5%, respectively. No special permission was required from the government for the field collection because none of the collected species or specimens were endangered.

Coccinella septempunctata cultures

Immature and adult *C septempunctata* collected from the field (Ayub Agricultural Research Institute, Faisalabad, Pakistan, 31°23′15.761″N; 73°2′59.772″E), were shifted to cages (45× 45 × 45 cm) in the laboratory, provided with ample supply of nymphs of respective aphid species from already established aphid cultures and maintained under the laboratory conditions of 24 ± 1°C, 70 ± 5% and 16: 8 hrs (L:D). One generation was reared, after which the eggs and pupae were separated from the culture. Pupae were transferred to Petri dishes (90 mm × 10 mm) (*Ali & Rizvi, 2010*), whereas the eggs were placed on water-soaked tissue paper in an incubator under similar laboratory conditions. The emerging adults and first-instar larvae were provided with a continuous supply of immature aphids (*Arif et al., 2011*).

For life table studies, 50 eggs from the above-maintained cultures were incubated in Petri dishes maintained at the above-mentioned laboratory conditions (*Ali & Rizvi, 2010*). The eggs were monitored at 12-h intervals. The emerging larvae were individually transferred to separate Petri dishes and initially fed on the first and second instars of prey species. The subsequent larval instars were fed on third and fourth instar aphids. The larvae were monitored at 12-h intervals until they pupated. Adult male–female pairs were allowed to mate for 24 h, after which the males were transferred to separate Petri dishes for longevity studies, and the gravid females were monitored until death regarding reproductive duration, longevity, and oviposition. The fecundity (number of eggs produced) and survival of every individual were monitored daily until death (*Zhao et al., 2015*). The developmental period, fecundity, adult preoviposition period (APOP), and total preoviposition period (TPOP) were evaluated based on the two-sex age-stage life table (*Chi, 1988*; *Huang & Chi, 2012*) with the TWOSEX-MSChart program (*Chi, 2013*). The age-specific survival rate and life expectancy were calculated as described by *Chi & Liu (1985)* and *Chi & Su (2006)*, respectively. To estimate the total population growth on different aphid species, the initial *C. septempunctata* populations (derived from 50 eggs) were projected to 60 days.

Statistical analysis

The duration of the developmental stages and the population parameters were calculated with the TWOSEX-MSChart program (*Chi, 2013*). The age-stage two-sex life table is useful because it enables users to precisely describe population characteristics, while also considering differences among stages and between sexes (*Zheng et al., 2017*). To minimize the variability in the results, the mean and standard error of the population were calculated according to a bootstrap procedure with 100,000 replications (*Efron & Tibshirani, 1993*). The population size was projected based on the two-sex age-stage life table data with the TIMING-MSChart program (*Chi, 2016*). The life table parameters calculated from raw data are presented in Table 1.

RESULTS

The mean developmental periods of the *C. septempunctata* growth stages are presented in Table 2. Starting from the egg stage, *C. septempunctata* reached the adult stage most quickly when reared on *R. padi* (16.49 days) and *S. avenae* (20.62 days). The pre-adult

Table 1 The description of life table parameters. The description of life table parameters calculated by TWOSEX-MSChart program.

Sr #	Parameters	Equation	
1	Age-specific survival rate (l_x)	$l_x = \sum_{j=1}^{k} s_{xj}$	The number of individuals surviving to age x where k is the number of stages
2	Age-specific fecundity (m_x)	$m_x = \frac{\sum_{j=1}^{k} s_{xj} f_{xj}}{\sum_{j=1}^{k} s_{xj}}$	It is expressed as the number of female offspring per female of age x where k is the number of stages
3	Net reproductive rate (R_0)	$R_0 = \sum_{x=0}^{\infty} l_x m_x$ or $R_0 = N_f/N \times F$	The total number of offspring that an average individual (including females, males, and those died in immature stage) can produce during its lifetime. The magnification that a population will increase after one generation.
4	Finite rate of increase (λ)	$\lambda = e^r$	The finite rate is the population growth rate as the time approaches infinity and the population reaches the stable age-stage distribution. The population size will increase at the rate of λ per time unit. or Number of females that produce one female per day (*Birch, 1948*).
5	Intrinsic rate of increase (r)	$\sum_{x=0}^{\infty} e^{-r(x+1)} l_x m_x = 1$	It is the population growth rate as time approaches infinity and the population reaches the stable age stage distribution. The population size will increase at the rate of e^r per time unit. or The maximum exponential multiplication rate of the whole population.
6	Life expectancy (e_{xj})	$e_{xj} = \sum_{i=x}^{\infty} \sum_{y=j}^{\beta} s_{iy}$	It is the time that an individual of age x and stage y is expected to live, where is the probability that individuals of age x and stage j will survive to age i and stage y and, is calculated by assuming $= 1$
7	Reproductive value (v_{xj})	$v_{xj} = \frac{e^{r(x+1)}}{s_{xj}} \sum_{i=x}^{\infty} e^{-r(i+1)} \sum_{y=j}^{\beta} s_{iy} f_{iy}$	The contribution of individuals of age x and stage y to the future population.
8	Mean generation time (T)	$T = ln R_0/r$	It is the period that a population requires to increase to R-fold of its size as time approaches infinity and the population settles down to a stable age-stage distribution. or The time that passes between first and next-generation oviposition.

developmental period of *C. septempunctata* was significantly longer (22.83 days) when reared on *R. maidis*. Regarding adult longevity, the adult females reared on *R. maidis* and *S. graminum* lived significantly longer than those reared on *S. avenae* and *R. padi*. The longevity of adult males was highest when reared on *R. maidis*, followed by *S. graminum*, *S. avenae*, and *R. padi*.

The adult and total preoviposition period of *C. septempunctata* reared on the four aphid species were also examined. The APOP refers to the duration from adult emergence to the first reproduction by females, whereas the TPOP refers to the period from birth (when the egg is laid) to the first reproduction by females. The results are presented in Table 3. The APOP was maximized by feeding on *R. maidis* and minimized by feeding on *R. padi*. Similarly, the TPOP was shortest and longest when *C. septempunctata* was fed on *R. padi* and *R. maidis*, respectively. The maximum daily and lifelong fecundities

Table 2 **Duration (days) of the developmental stages.** Duration (days) of the developmental stages of *C. septempunctata* reared on four aphid species.

Stages	Developmental time (Mean ± SE)							
	n^b	*R. padi*	n^b	*R. maidis*	n^b	*S. avenae*	n^b	*S. graminum*
Egg	50	3.56 ± 0.07d	50	5.54 ± 0.07a	50	4.00 ± 0.00c	50	5.00 ± 0.00b
L1	45	2.00 ± 0.00c	46	3.12 ± 0.09a	48	3.04 ± 0.12b	45	3.00 ± 0.00b
L2	43	2.00 ± 0.00c	43	3.16 ± 0.07a	42	3.09 ± 0.10a	40	3.00 ± 0.00b
L3	38	2.47 ± 0.09b	34	3.32 ± 0.08a	34	3.09 ± 0.09b	35	3.06 ± 0.04b
L4	35	2.29 ± 0.08c	32	3.34 ± 0.10a	28	3.07 ± 0.07b	31	3.06 ± 0.04b
Pre-pupa	34	1.00 ± 0.00a	31	1.00 ± 0.00a	28	1.00 ± 0.00a	30	1.00 ± 0.00a
Pupa	29	3.17 ± 0.10c	23	4.35 ± 0.12a	27	3.33 ± 0.09c	24	3.62 ± 0.10b
Pre-adult duration	29	16.38 ± 0.23d	23	24.09 ± 0.27a	27	20.81 ± 0.27c	24	21.71 ± 0.11b
Adult Longevity								
Female	19	48.16 ± 0.43c	16	58.12 ± 0.44a	18	50.22 ± 0.48b	17	57.47 ± 0.27a
Male	10	37.1 ± 0.66c	7	46.56 ± 0.40a	9	40.56 ± 0.58b	7	45.71 ± 0.29a

Notes.
L1–L4 refers to the first-to-fourth larval instars. [b] number of individual *C. septempunctata* that completed the indicated stage. Values with similar letters in a row are statistically non-significant at the 5% confidence level. The standard error (SE) was estimated by bootstrapping (100,000 replications).

Table 3 **Comparison of reproduction and life table parameters.** Comparison of reproduction and life table parameters [mean standard error (SE)] of *C. septempunctata* reared on four aphid species.

Parameters	*R. padi*	*R. maidis*	*S. avenae*	*S. graminum*
APOP	3.26 ± 0.10b	4.44 ± 0.13a	3.56 ± 0.12b	3.47 ± 0.34b
TPOP	19.84 ± 0.29c	28.94 ± 0.35a	24.67 ± 0.35b	25.24 ± 0.4b
Oviposition days	25.16 ± 0.35b	24.62 ± 0.47b	22.22 ± 0.3c	27.59 ± 0.37a
Fecundity (eggs per female)	760.05 ± 4.25a	348.94 ± 2.16c	345.39 ± 3.4c	529.00 ± 3.43b
Daily fecundity (maximum)	72	48	36	57
Lifelong fecundity (maximum)	787	360	370	553
R_0 (offspring individual^{-1})	289.04 ± 52.15a	111.68 ± 23.01b	124.27 ± 23.48b	179.77 ± 35.46ab
T (days)	29.02 ± 0.34d	39.75 ± 0.37a	34.29 ± 0.31c	36.02 ± 0.17b
r (d)	0.1946 ± 0.0072a	0.1180 ± 0.0057c	0.1400 ± 0.0061b	0.1435 ± 0.0060b
λ (d^1)	1.2149 ± 0.0087a	1.1253 ± 0.0064c	1.1504 ± 0.0070b	1.1543 ± 0.0069b

Notes.
Values with similar letters in a row are statistically non-significant at the 5% confidence level. The standard error (SE) was estimated by bootstrapping (100,000 replications).
APOP, adult pre-ovipositional period; TPOP, total pre-ovipositional period (time from birth to the first reproduction by females); R_0, net reproductive rate; r, intrinsic rate of increase; T, mean generation time; λ, finite rate of increase.

of *C. septempunctata* (recorded as the number of eggs laid) also depended on the aphid species. Specifically, the highest and lowest fecundities were recorded for specimens reared on *R. padi* and *R. maidis*, respectively.

As indicated in Fig. 1, the age-stage-specific survival rate of adult females was high when reared on *R. padi*, *S. avenae*, and *S. graminum*, but decreased when reared on *R. maidis*. Moreover, the l_x, f_{xj}, and m_x curves revealed the survival rate and fecundity were the highest when *C. septempunctata* was reared on *R. padi*. The maximum daily fecundity (60.78 eggs) was observed for *C. septempunctata* reared on *R. padi* at 30 days post-hatching. The second highest f_{xj} peak was observed for *C. septempunctata* reared on *S. graminum* (50.64 eggs
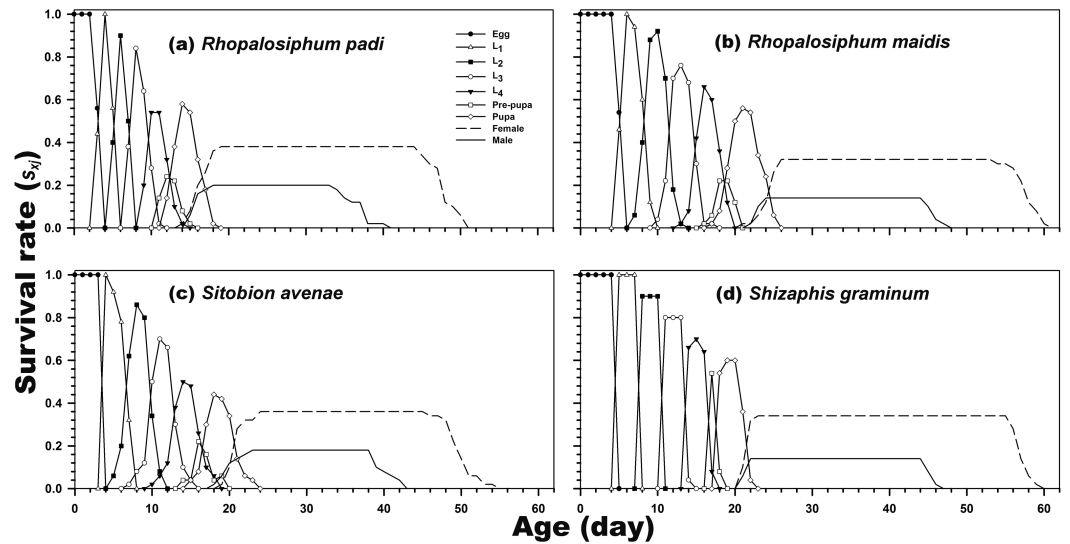
Figure 1 Age-stage-specific survival rate (s_{xj}) of *C. septempunctata* reared on four aphid species. (A) *Rhopalosiphum padi*, (B) *Rhopalosiphum maidis*, (C) *Sitobion avenae*, (D) *Schizaphis graminum*.
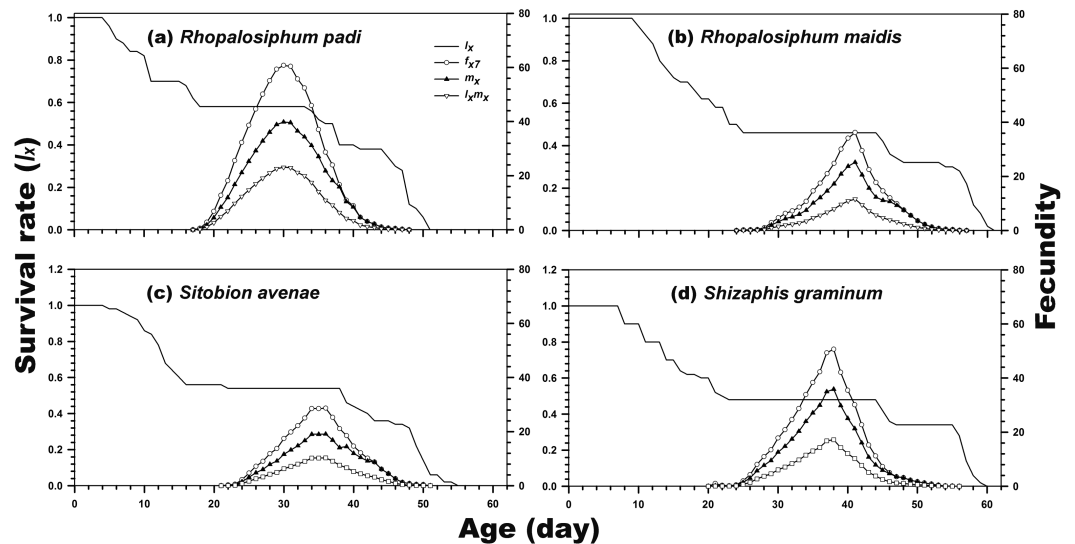
Figure 2 Age-specific survival rate (l_x), age-stage-specific female fecundity (f_{xj}), age-specific fecundity (m_x), and age-specific net maternity ($l_x m_x$) of *C. septempunctata* reared on four aphid species. (A) *Rhopalosiphum padi*, (B) *Rhopalosiphum maidis*, (C) *Sitobion avenae*, (D) *Schizaphis graminum*.

at 38 days post-hatching). The least daily fecundity was observed when fed on *S. avenae* (28.67 eggs at 36 days post-hatching), which was less than half when fed on *R. padi* (Fig. 2).

The results revealed that newly hatched larvae can survive for 34.06, 30.32, 31.04, and 33.50 days when reared on *R. maidis*, *R. padi*, *S. avenae*, and *S. graminum*, respectively. Regardless of the prey species, life expectancy was higher for adult females than for adult males. The female and male life expectancies were highest when reared on *R. maidis* (37.13
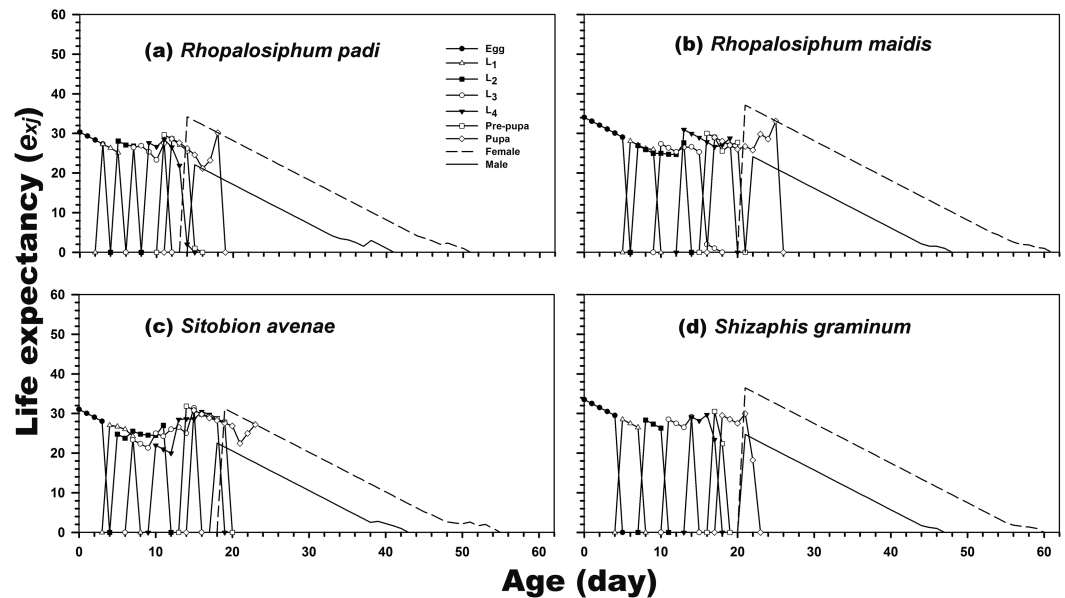
Figure 3 **Age-stage-specific life expectancy (e_{xj}) of *C. septempunctata* reared on four aphid species.**
(A) *Rhopalosiphum padi*, (B) *Rhopalosiphum maidis*, (C) *Sitobion avenae*, (D) *Schizaphis graminum*.

and 24.14 days after 20 and 21 days of rearing, respectively) and *S. graminum* (36.47 and 24.71 days, respectively, after 21 days of rearing) (Fig. 3).

Reproduction was possible only during the adult female stage. The highest age-stage-specific reproductive rates of the newly hatched individuals (1.21) and adult females (266.47; after 27 days) were calculated after rearing on *R. padi*. In contrast, the reproductive rate of *C. septempunctata* reared on *S. avenae* was highest (144.83) after 31 days. For the *C. septempunctata* reared on *R. padi*, the v_{xj} of the egg stage was related to the rate of the population increase (1.214 per day) (Fig. 4).

Population parameters

The population parameters, including net reproductive rate (R_0), intrinsic rate of increase (r), finite rate of increase (λ), and mean generation time (T), of *C. septempunctata*, reared on various aphid species are provided in Table 3. The means and standard errors of these population parameters were estimated with a bootstrap procedure involving 100,000 replications. Additionally, R_0, r, and λ of *C. septempunctata* reared on the four aphid species decreased in the following rank order: *R. padi* >*S. graminum* >*S. avenae* >*R. maidis*. The mean generation time was maximized and minimized when *C. septempunctata* was reared on *R. maidis* and *R. padi*, respectively.

Population projection

Figure 5, which was prepared with the TIMING MS-Chart program, presents the population projection of *C. septempunctata* under conditions unaffected by biotic and abiotic factors predicted at 60 days post-hatching. The highest predicted logarithms of the total population
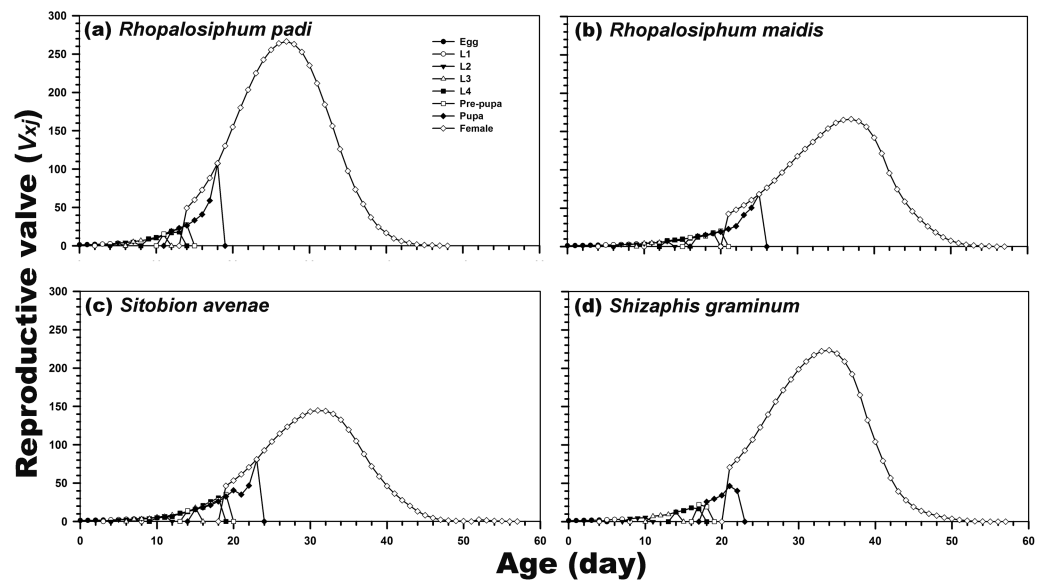
Figure 4 Age-stage-specific reproductive rate (v_{xj}) of *C. septempunctata* reared on four aphid species. (A) *Rhopalosiphum padi*, (B) *Rhopalosiphum maidis*, (C) *Sitobion avenae*, (D) *Schizaphis graminum*.

sizes were observed when reared on *R. padi* (5.51) and *R. maidis* (2.89) whereas much lower when reared on *S. graminum* and *S. avenae*.

DISCUSSION

Prey quality influences the survival, fecundity, and longevity of predators (*Moghaddam et al., 2016*). Additionally, the nature and quality of the prey significantly affect the egg incubation period and larval instars of *C. septempunctata* (*Majerus & Kearns, 1989*). A previous study revealed that coccinellids provided low-quality food exhibited delayed development, whereas rearing on high-quality food had the opposite effect (*Snyder et al., 2000*). In the current study, the longest developmental period and the highest adult longevity were observed for *C. septempunctata* reared on *R. maidis*. *Rhopalosiphum maidis* is a weakly suitable prey for *C. septempunctata*, which is consistent with the results of a previous study by *Obrycki & Orr (1990)*. They determined that the larval period was longer when *C. septempunctata* was reared on *R. maidis* than when it was reared on *Acyrthosiphon pisum* Harris (Hemiptera: Aphididae). Moreover, adult *C. septempunctata* beetles derived from larvae reared on *R. maidis* were smaller and lighter than those reared on *A. pisum*. Prey quality affects the larval and adult developmental periods (*Farooq et al., 2018*), both of which are feeding stages, and our results provide evidence that predators consume the most palatable host species. The increased growth, development, and survival rate of *C. septempunctata* that fed on *L. erysimi* was due to the relatively high protein contents of this species (*Srivastava, 2003*).

Food quality also affects the potential of females to lay eggs. For example, coccinellid fecundity reportedly decreases as the availability of food decreases (*Kajita & Evans, 2009*).
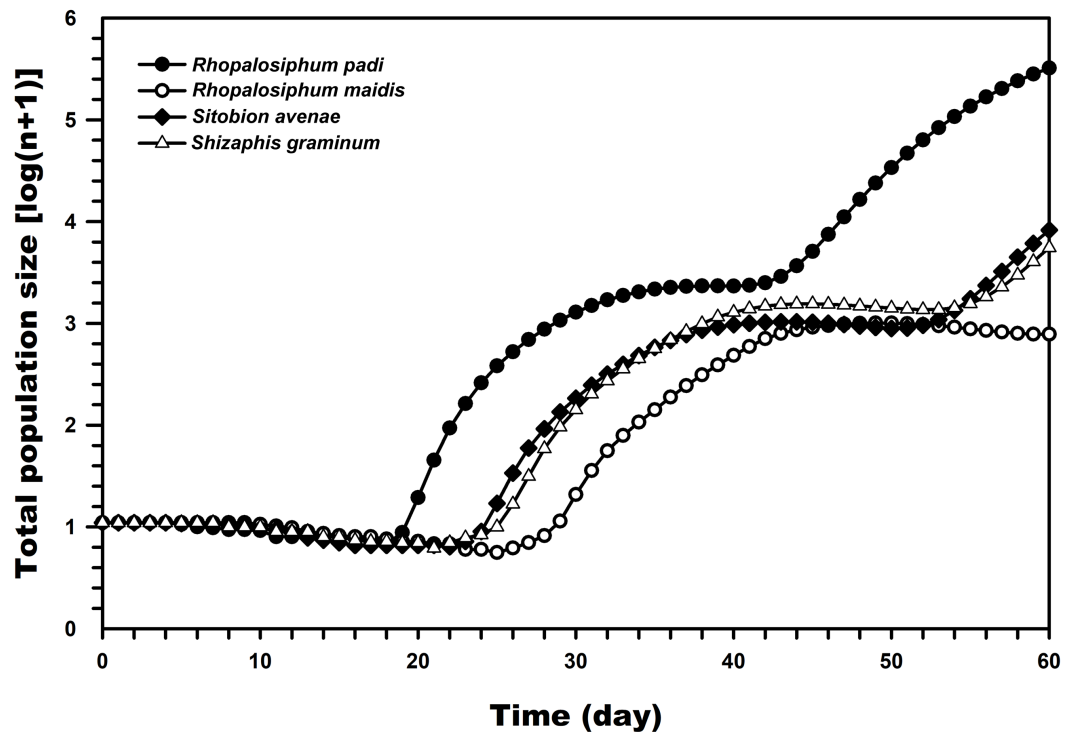
Figure 5 Comparison of the population projections of *C. septempunctata* reared on four aphid species, based on the age-stage two-sex life table.

Hodek & Honek (1996) revealed that the fecundity of a predator is influenced by the rearing conditions and the nutritional value of prey. Additionally, the daily oviposition and clutch size, but not the egg size, is affected by variations in the food supply (*Dixon & Guo, 1993*). *Dixon & Dixon (2000)* reported that the fecundity and longevity of a predator may be related. In confined environments, egg production is enhanced by a high prey density. *Evans (2000)* revealed that predators prefer to lay eggs in regions with a high abundance of prey items to ensure an adequate food supply for their progeny. Additionally, some vulnerable juveniles complete their development quickly to minimize the risk of self-predation (*Santos et al., 2013*).

The data presented herein confirm that biological parameters (e.g., developmental duration, adult longevity, and reproduction) of *C. septempunctata* are considerably manipulated by the type of prey species. The combined effects of the biological parameters are consequently indicated by the *C. septempunctata* population parameters (r, λ, R_0, and T). In the current study, we observed that *C. septempunctata* reared on *R. padi* produced the highest r, λ, and R_0, implying the nutritional quality varied among the four tested aphid species. These results could be compared with the previous findings of *Farooq et al. (2018)* that life table parameters varied significantly with respect to the difference in food quality where *M. persicae* was found to be the most suitable host for rearing of *C. septempunctata*.

The intrinsic rate of increase (r) is the most important parameter for comparing the growth potentials of a population under diverse circumstances (*Southwood, 1966*). *Lewontin*

(1965) reported that the intrinsic rate of increase should be high for predators with a short pre-ovipositional period. *Zhao et al. (2015)* proved that *Cheilomenes* (*Menochilus*) *sexmaculata* Fabricius (Coleoptera: Coccinellidae) has a shorter TPOP under laboratory conditions than under semi-natural conditions. In our study, *C. septempunctata* fed on *R. padi* had the shortest TPOP. The TPOP is an important factor for biological control methods because a short TPOP implies the predator will promptly invade aphids in the field. Any inconsistencies with the findings of previous studies may be due to changes to the biotic and abiotic components.

The survival rate (s_{xj}) not only describes the survival in detail, but it also indicates the differences and changes in the developmental stages of a cohort (*Ali & Rizvi, 2010*; *Chi & Su, 2006*). In the present study, the survival rate was highest for *C. septempunctata* reared on *R. padi*. Moreover, the survival rate decreased over time. *Yu, Chi & Chen (2005)* reported that *Lemnia biplagiata* (Coleoptera: Coccinellidae) survives longer on *Aphis gossypii* under confined laboratory conditions than under field conditions, which is relevant for our study as well.

Rhopalosiphum padi and *R. maidis* were assessed as the most and least suitable hosts, respectively, for *C. septempunctata*, despite both species belonging to the same genus. This may reflect the differences in the resistance to predation and nutrient contents between *R. padi* and *R. maidis* (*Chi, 2013*). The host plant may affect the palatability and suitability of aphid species to ladybird beetles (*Zheng et al., 2017*).

CONCLUSIONS

The demographic parameters of *C. septempunctata* varied when reared on different host aphid species. Interestingly, *R. padi* was assessed as the most suitable host, while *R. maidis* was the least suitable. The results in the study indicated that demographic analysis of predator development, survival, and reproduction based on the age stage, two-sex life table offers a comprehensive assessment of predator growth potential on different host aphid species. This information will be valuable for understanding the population ecology of *C. septempunctata,* enabling the successful mass-rearing of the predator in the laboratory. The results also support the possible use of *C. septempunctata* as a biocontrol agent against aphids in the field.

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Competing Interests

The authors declare there are no competing interests.

Author Contributions

- Muhammad Farooq and Xun Zhu analyzed the data, conceived and designed the experiments, performed the experiments, prepared figures and/or tables, and approved the final draft.
- Muhammad Shakeel conceived and designed the experiments, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft.
- Ayesha Iftikhar analyzed the data, prepared figures and/or tables, and approved the final draft.
- Muhammad Rafiq Shahid analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft.
- Nadia Saeed analyzed the data, conceived and designed the experiments, authored or reviewed drafts of the paper, and approved the final draft.
- Muhammad Shahid Arain analyzed the data, conceived and designed the experiments, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft.

Data Availability

The raw measurements are available as a Supplementary Files.

Supplemental Information

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REFERENCES

Akram W, Akbar S, Mehmood A. 1996. Studies on the biology and predatory efficacy of *Coccinella septempunctata* with special reference to cabbage. *Pakistan Entomologist* **18**:104–106.

Ali A, Rizvi PQ. 2007. Development and predatory performance of *Coccinella septempunctata* L.(Coleoptera: Coccinellidae) on different aphid species. *Journal of Biological Sciences* **7**:1478–1483 DOI 10.3923/jbs.2007.1478.1483.

Ali A, Rizvi PQ. 2010. Age and stage-specific life table of *Coccinella septempunctata* (Coleoptera: Coccinellidae) at varying temperatures. *World Journal of Agricultural Sciences* **6**:268–273.

Arif MJ, Gogi MD, Abid AM, Imran M, Shahid MR, Husain S, Arshad M. 2011. Predatory potential of some native coccinellid predators against *Phenacoccus solenopsis*, Tinsely (Pseudococcidae: Hemiptera). *Pakistan Entomologist* **33**:97–103.

Arshad A, Parez O. 2007. Development and predatory performance of *Coccinella septempunctata* L. (Coleoptera: Coccinellidae) on different aphid species. *Journal of Biological Sciences* **1**:1–6.

Birch L. 1948. The intrinsic rate of natural increase of an insect population. *Journal of Animal Ecology* **17**:15–26 DOI 10.2307/1605.

Blackman R. 1967. Selection of aphid prey by *Adalia bipunctata* L., and *Coccinella septempunctata* L. *Annals of Applied Biology* **59**:331–338 DOI 10.1111/j.1744-7348.1967.tb04449.x.

Chi H. 1988. Life-table analysis incorporating both sexes and variable development rates among individuals. *Environmental Entomology* **17**:26–34 DOI 10.1093/ee/17.1.26.

Chi H. 2013. TWO SEX-MSChart: a computer program for age stage, two-sex life table analysis. *Available at http://140.120.197.173/ecology/prod02.htm*.

Chi H. 2016. TIMING-MSChart: a computer program for the population projection based on age-stage, two-sex life table. *Available at http://140.120.197.173/ecology/prod02.htm*.

Chi H, Liu H. 1985. Two new methods for the study of insect population ecology. *Bulletin of the Institute of Zoology, Academia Sinica* **24**:225–240.

Chi H, Su HY. 2006. Age-stage, two-sex life tables of *Aphidius gifuensis* (Ashmead)(Hymenoptera: Braconidae) and its host *Myzus persicae* (Sulzer)(Homoptera: Aphididae) with mathematical proof of the relationship between female fecundity and the net reproductive rate. *Environmental Entomology* **35**:10–21 DOI 10.1603/0046-225X-35.1.10.

Chi H, Yang TC. 2003. Two-sex life table and predation rate of *Propylaea japonica* Thunberg (Coleoptera: Coccinellidae) fed on *Myzus persicae* (Sulzer)(Homoptera: Aphididae). *Environmental Entomology* **32**:327–333 DOI 10.1603/0046-225X-32.2.327.

Conti BFD, Bueno VHP, Sampaio MV, Sidney LA. 2010. Reproduction and fertility life table of three aphid species (Macrosiphini) at different temperatures. *Revista Brasileira de Entomologia* **54**:654–660 DOI 10.1590/S0085-56262010000400018.

Cranshaw W, Jevremovic Z, Sclar DC, Mannix L. 2000. Observations on the biology and control of the hawthorn (two-circuli) mealybug, *Phenacoccus dearnessi* (King). *Journal of Arboriculture* **26**:225–229.

Divender G, Ranjeet B, Gupta D, Bhatia R. 2000. Population dynamics of the citrus psylla, *Diaphorina citri* Kuwayama, in lower hills of Himachal Pradesh. *Pest Management and Economic Zoology* **8**:41–45.

Dixon AFG, Dixon AE. 2000. *Insect predator–prey dynamics: ladybird beetles and biological control.* Cambridge, United Kingdom: Cambridge University Press.

Dixon AFG, Guo Y. 1993. Egg and cluster size in ladybird beetles (Coleoptera: Coccinellidae): the direct and indirect effects of aphid abundance. *European Journal of Entomology* **90**:457–463.

Efron B, Tibshirani RJ. 1993. *An introduction to the bootstrap.* New York: Chapman & Hall.

Evans EW. 2000. Morphology of invasion: body size patterns associated with establishment of *Coccinella septempunctata* (Coleoptera: Coccinellidae) in western North America. *European Journal of Entomology* **97**:469–474 DOI 10.14411/eje.2000.072.

Farooq M, Shakeel M, Iftikhar A, Shahid MR, Zhu X. 2018. Age-stage, two-sex life tables of the lady beetle (Coleoptera: Coccinellidae) feeding on different aphid species. *Journal of Economic Entomology* **111**:575–585 DOI 10.1093/jee/toy012.

Gupta RK, Pervez A, Guroo MA, Srivastava K. 2012. Stage-specific functional response of an aphidophagous ladybird, Coccinella septempunctata (Coleoptera: Coccinellidae), to two aphid species. *International Journal of Tropical Insect Science* **32**:136–141 DOI 10.1017/S1742758412000227.

Gusev G, Svikle MY, Sorokin N, Koval A, Prisnïi YV. 1983. Effectiveness of field populations of natural enemies of the Colorado beetle. In: Novozhilov KV, ed. *Biotsenoticheskoe obosnovanie kriteriev effektivnosti prirodnykh entomofagov.* Lenina Leningrad USSR: Vsesoyuznaya Akademiya Sel'skokhozyaĭstvennykh Nauk im. V.I, 70–79.

Hauge MS, Nielsen FH, Toft S. 1998. The influence of three cereal aphid species and mixed diet on larval survival, development and adult weight of *Coccinella septempunctata*. *Entomologia Experimentalis et Applicata* **89**:319–322 DOI 10.1046/j.1570-7458.1998.00415.x.

Hodek I, Honek A. 1996. *Ecology of Coccinellidae Kluwer.* Dordrecht: Springer, Netherlands 978–994.

Honek A, Martinkova Z. 2005. Long term changes in abundance of *Coccinella septempunctata* (Coleoptera: Coccinellidae) in the Czech Republic. *European Journal of Entomology* **102**:443–448 DOI 10.14411/eje.2005.063.

Huang YB, Chi H. 2012. Age-stage, two-sex life tables of *Bactrocera cucurbitae* (Coquillett)(Diptera: Tephritidae) with a discussion on the problem of applying female age-specific life tables to insect populations. *Insect Science* **19**:263–273 DOI 10.1111/j.1744-7917.2011.01424.x.

Kajita Y, Evans EW. 2009. Ovarian dynamics and oosorption in two species of predatory lady beetles (Coleoptera: Coccinellidae). *Physiological Entomology* **34**:185–194 DOI 10.1111/j.1365-3032.2009.00674.x.

Kalushkov P, Hodek I. 2004. The effects of thirteen species of aphids on some life-history parameters of the ladybird *Coccinella septempunctata*. *BioControl* **49**:21–32 DOI 10.1023/B:BICO.0000009385.90333.b4.

Kawauchi S. 1985. Comparative studies on the fecundity of three aphidophagous coccinellids (Coleoptera: Coccinellidae). *Japanese Journal of Applied Entomology and Zoology* **29**:203–209 DOI 10.1303/jjaez.29.203.

Khanamani M, Fathipour Y, Hajiqanbar H. 2013. Population growth response of *Tetranychus urticae* to eggplant quality: application of female age-specific and age-stage, two-sex life tables. *International Journal of Acarology* **39**:638–648 DOI 10.1080/01647954.2013.861867.

Krafsur ES, Obrycki JJ, Harwood JD. 2005. Comparative genetic studies of native and introduced Coccinellidae in North America. *European Journal of Entomology* **102**:469–474 DOI 10.14411/eje.2005.067.

Kumar R, Gupta P. 2006. Natural enemies associated with the greenhouse whitefly, *Trialeurodes vaporariorum* (Westwood), on vegetable crops in the mid-hill region of Himachal Pradesh. *Pest Management and Economic Zoology* **14**:73–78.

Lakhanpal GC, Raj D. 1998. Predation potential of coccinellid and syrphid on important aphid species infesting rapeseed in Himachal Pradesh. *Journal of Entomological Research* **22**:181–190.

Lewontin RC. 1965. Selection for colonizing ability. In: *The genetics of colonizing species: proceedings of the first International union of biological sciences symposia on general biology.* New York, United States: Academic Press, 77–94.

Majerus M, Kearns P. 1989. *Ladybirds, naturalist handbook 10.* Dorset: The Richmond Publishing Co Ltd.

Marin J, Crouau-Roy B, Hemptinne JL, Lecompte E, Magro A. 2010. *Coccinella septempunctata* (Coleoptera, Coccinellidae): a species complex? *Zoologica scripta* **39**:591–602 DOI 10.1111/j.1463-6409.2010.00450.x.

Moghaddam MG, Golizadeh A, Hassanpour M, Rafiee-Dastjerdi H, Razmjou J. 2016. Demographic traits of *Hippodamia variegata* (Goeze)(Coleoptera: Coccinellidae) fed on *Sitobion avenae* Fabricius (Hemiptera: Aphididae). *Crop Protection* **5**:431–445 DOI 10.18869/modares.jcp.5.3.431.

Obrycki JJ, Orr CJ. 1990. Suitability of three prey species for Nearctic populations of *Coccinella septempunctata, Hippodamia variegata,* and *Propylea quatuordecimpunctata* (Coleoptera: Coccinellidae). *Journal of Economic Entomology* **83**:1292–1297 DOI 10.1093/jee/83.4.1292.

Omkar , Pervez A. 2002. Ecology of aphidophagous ladybird beetle, *Coccinella septempunctata* Linn. (Coleoptera: Coccinellidae): a review. *Journal of Aphidology* **16**:175–201.

Omkar , Srivastava S, James B. 1997. Prey preference of a lady beetle, *Coccinella septempunctata* Linnaeus (Coleoptera: Coccinellidae). *Journal of Advances in Zoology* **18**:96–97.

Ramalho FS, Malaquias JB, Lira AC, Oliveira FQ, Zanuncio JC, Fernandes FS. 2015. Temperature-dependent fecundity and life table of the fennel aphid *Hyadaphis foeniculi* (Passerini) (Hemiptera: Aphididae). *PLOS ONE* **10**:e0122490 DOI 10.1371/journal.pone.0122490.

Reddy GV, Chi H. 2015. Demographic comparison of sweet potato weevil reared on a major host, *Ipomoea batatas*, and an alternative host, *I. triloba*. *Scientific Reports* **5**:11871 DOI 10.1038/srep11871.

Santos LC, Santos-Cividanes TM, Cividanes FJ, Matos STS. 2013. Biological aspects of *Harmonia axyridis* in comparison with *Cycloneda sanguinea* and *Hippodamia convergens*. *Pesquisa Agropecuária Brasileira* **48**:1419–1425 DOI 10.1590/S0100-204X2013001100001.

Sarwar M, Saqib SM. 2010. Rearing of predatory seven spotted ladybird beetle *Coccinella septempunctata* L.(Coleoptera: Coccinellidae) on natural and artificial diets under laboratory conditions. *Pakistan Journal of Zoology* **42**:47–51.

Shannag HK, Obeidat WM. 2008. Interaction between plant resistance and predation of *Aphis fabae* (Homoptera: Aphididae) by *Coccinella septempunctata* (Coleoptera: Coccinellidae). *Annals of Applied Biology* **152**:331–337 DOI 10.1111/j.1744-7348.2008.00220.x.

Snyder WE, Joseph SB, Preziosi R, Moore AJ. 2000. Nutritional benefits of cannibalism for the lady beetle *Harmonia axyridis* (Coleoptera: Coccinellidae) when prey quality is poor. *Environmental Entomology* **29**:1173–1179 DOI 10.1603/0046-225X-29.6.1173.

Solangi BK, Lohar MK, Abro G, Talpur M. 2007. Searching ability and feeding potential of larvae, 7-spotted beetle *Coccinella septempunctata* Linn. under laboratory and field conditions. *Sarhad Journal of Agriculture* **23**:705–711.

Southwood R. 1966. *Ecological methods: with particular reference to the study of insect populations.* Methuen, London: T.R.E. Southwood.

Suhail A, Sabir AM, Hussain A, Saeed A. 1999. Predatory efficacy of *Coccinella septempunctata* L., on cotton aphids, *Aphis gossypii* Glov. *Pakistan Journal of Biological Sciences* **2**:603–605 DOI 10.3923/pjbs.1999.603.605.

Triltsch H. 1999. Food remains in the guts of *Coccinella septempunctata* (Coleoptera: Coccinellidae) adults and larvae. *European Journal of Entomology* **96**:355–364.

Yu J-Z, Chi H, Chen B-H. 2005. Life table and predation of *Lemnia biplagiata* (Coleoptera: Coccinellidae) fed on *Aphis gossypii* (Homoptera: Aphididae) with a proof on relationship among gross reproduction rate, net reproduction rate, and preadult survivorship. *Annals of Entomological Society of Amsterdam* **98**:475–482 DOI 10.1603/0013-8746(2005)098[0475:LTAPOL]2.0.CO;2.

Zhang GF, Lü ZC, Wan FH. 2007. Detection of *Bemisia tabaci* remains in predator guts using a sequence-characterized amplified region marker. *Entomologia Experimentalis et Applicata* **123**:81–90 DOI 10.1111/j.1570-7458.2007.00528.x.

Zhao J, Li S, Gao X-W, Zhang F, Wang S. 2015. Comparison of life tables of *Cheilomenes sexmaculata* (Coleoptera: Coccinellidae) under laboratory and greenhouse conditions. *Journal of Economic Entomology* **108**:1700–1707 DOI 10.1093/jee/tov178.

Zheng X-M, Tao Y-L, Chi H, Wan F-H, Chu D. 2017. Adaptability of small brown planthopper to four rice cultivars using life table and population projection method. *Scientific Reports* **7**:42399 DOI 10.1038/srep42399.