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Temperature-Dependent Demographic Parameters of *Diaeretiella rapae* (M'Intosh, 1855) (Hymenoptera: Braconidae) on *Schizaphis graminum* (Rondani, 1852) (Hemiptera: Aphididae)

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ABSTRACT

Diaeretiella rapae (M'Intosh) (Hymenoptera: Braconidae) is one of the most important biological control agents of aphids on crucifer and cereal plants. The reproduction and demographic parameters of *D. rapae* were investigated at six constant temperatures (10, 15, 20, 25, 27.5, and 30 °C) on the greenbug, *Schizaphis graminum* (Rondani) (Hemiptera: Aphididae) reared on wheat (var. Pishtaz). No development was observed at 30 °C. The highest value of mummified aphids per parasitoid female was obtained at temperature of 20 °C (120.08). However, the highest (0.374 day^{-1}) and lowest (0.019 day^{-1}) values of the intrinsic rate of increase (*r*) were observed at 25 and 27.5 °C, respectively. The shortest times for doubling and mean generation of parasitoid were resulted at 25 °C (1.85 and 7.73 days, respectively). Based on the results, a range of 20 to 25 °C is the most suitable temperature regime for *D. rapae* population growth on *S. graminum*. These findings have potential implications for integrated *S. graminum* management in wheat fields. However, semi-field and field studies are needed to obtain more environmentally relevant results.

Keywords: biological control, parasitoid wasp, environmental condition, life table, intrinsic rate of increase.

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INTRODUCTION

The greenbug, *Schizaphis graminum* Rondani (Hemiptera: Aphididae), is a cosmopolitan and polyphagous aphid which is widely distributed in temperate regions. It is a major pest of cereal crops, particularly wheat (Blackman & Eastop, 2006; van Emden & Harrington, 2007; Jokar, Zarabi, Shahrokhi, & Rezapanah, 2012; Zogli et al, 2020). Damage caused by this species not only weakens the plant, but also transmits viral and phytoplasma diseases ultimately ending up with plant mortality, if the aphid population is not sufficiently controlled (Tofangsazi, Kheradmand, Shahrokhi, & Talebi, 2011; Rezaei et al, 2020b; Zogli et al, 2020). To control aphid infestations, chemical pesticides are commonly used in cereal cultivation. The indiscriminate use of pesticides has led to development of aphid's resistance and decrement of the populations of natural enemies (Jokar et al, 2012; Tazerouni, Talebi, & Rakhshani, 2012; Rezaei & Moharramipour, 2019; Kazemi et al, 2020). Biological control, in particular the augmentative release of biocontrol agents, is an appropriate alternative method to control the aphid infestations (Boivin, Hance, & Brodeur, 2012; Rezaei et al, 2020a).

Among biological control agents, *Diaeretiella rapae* (M'Intosh) (Hymenoptera: Braconidae) has been reported to be an important parasitoid of aphids. It is a solitary and polyphagous endoparasitoid of aphids on crucifer and cereal plants (Silva, Cividanes, Pedroso, & Sala, 2011; Kazemi et al, 2020; Nisar & Rizvi, 2021). The origin of *D. rapae* is considered to be of Western Palearctic and it is currently spread in various parts of the world (Rakhshani et al, 2008; Singh & Singh, 2015). This biocontrol agent is known to parasitize over 98 species of aphids infesting more than 180 plant species belonging to 43 plant families distributed in 87 countries in the world (Bodlah, Naeem, & Mohsin, 2012; Singh & Singh, 2015; Farahani, Talebi, & Rakhshani, 2016). The most economically important hosts for *D. rapae* are *Brevicoryne brassicae* (L.) (Basheer, Aslan, & Asaad, 2014; Karami, Fathipour, Talebi, & Reddy, 2018), *Myzus persicae* (Sulzur) (Bodlah et al, 2012; Nisar & Rizvi, 2021), *Diuraphis noxia* (Mordvilko) (Tazerouni et al, 2012), *Lipaphis erysimi* (Kaltenbach) (Silva et al, 2011; Soni & Kumar, 2021), and *S. graminum* (Kazemi et al, 2020).

Knowledge of the adaptation of natural enemies to climatic conditions is required for predicting the survival and development time (Haghani, Fathipour, Talebi, & Baniameri, 2007; Rezaei et al, 2020b). Temperature is one of the most critical abiotic factors affecting biological traits of many arthropods including, developmental rate, survivorship, adult longevity, sex ratio, fecundity, and fertility (Hayakawa, Grafius, & Stehr, 1990; Haghani et al, 2007; Karimi-Malati, Fathipour, Talebi, & Bazoubandi, 2014; Mirhosseini, Fathipour, & Reddy, 2017; Rezaei et al, 2020a). In addition, some physiological attributes of insects, including extra molting and larval stadia, are influenced by temperature (Ismail et al, 2014; Karimi-Malati et al, 2014; Souza, Veloso, Sampaio, & Davis, 2017).

The biology of *D. rapae* has been studied on different host aphids including, *D. noxia* (Tazerouni et al, 2012), *M. persicae* (Bodlah et al, 2012; Ghorbanian, Fathipour, Talebi, & Reddy, 2019), *B. brassicae* (Karami et al, 2018), and *L. erysimi* (Silva et al, 2011; Nisar & Rizvi, 2021). However, some researchers have focused on development and fecundity of this parasitoid at a single constant temperature or a narrow range of different constant temperatures (Hayakawa et al, 1990; Bernal & Gonzalez, 1997; Tazerouni et al, 2012; Basheer et al, 2014; Souza et al, 2017). For instance, Tazerouni, Talebi, Rakhshani, & Zamani (2013) reported that the highest value of net reproductive rate (R_0) for *D. rapae* is obtained at 10 °C and the parasitoid is potentially able to control *D. noxia* at temperatures of 10 to 15 °C. In addition, Basheer et al (2014) indicated that the optimum temperature for *D. rapae* ranges from 20 to 25 °C based on the developmental rate and mortality. Talebi et al (2021) investigated the functional response of *D. rapae* reared on *S. graminum* at five constant temperatures (10, 15, 20, 25, and 30 °C); their results showed that the optimum temperatures range from 20 to 25 °C. Moreover, the demographic parameters of *D. rapae* at a wide range of temperatures especially on the greenbug, *S. graminum*, have not yet been reported.

The comprehensive knowledge of different biological parameters of *D. rapae* under variable environmental conditions is required to optimize aphid's biological control programs. Demographic parameters are important measurement of population growth potential of a species under specific conditions (Carey, 2001; Amiri, Talebi, Zamani, & Kamali, 2010; Rezaei et al, 2020a). Therefore, the main objective of this study was to elucidate the relationship between the demographic parameters and temperature for *D. rapae* on *S. graminum*. To do so, we compared temperature effects (10, 15, 20, 25, 27.5, and 30 °C) on the reproduction and life table parameters of *D. rapae*. Our study provides additional information on the biology of *D. rapae*, which may be helpful to improve biological control programs of this economically important aphid pest on cereals.

MATERIAL AND METHODS

Plant, host aphid, and parasitoid cultures

Original populations of both *S. graminum* and *D. rapae* were collected from wheat fields of Tarbiat Modares University, Tehran (35°44′N, 51°09′E, 1273 m above sea level) in April 2011. The colony of *S. graminum* was maintained on potted wheat seedlings (about 15 cm height). Seeds of wheat, *Triticum aestivum* L. var. Pishtaz, were obtained from the Seed and Plant Improvement Research Institute in Karaj, Iran. The seeds were planted in plastic pots (20 cm diameter; 13 cm high) without application of any fertilizers or pesticides under glasshouse conditions (25 ± 5ºC, 60 ± 5% RH and 16:8 h L:D photoperiod) until they reached three-week-old. A ventilated cylindrical acrylic plastic (20 cm diameter, 30 cm high) covered the wheat plants. In order to maintain the parasitoid colony, about 10 pairs of one-day-old *D. rapae* were released into the cylindrical plastic cage with wheat plants infested by *S. graminum*. After a 24 h exposure, the parasitoids were removed from the cylindrical plastic cage. Then, the aphids were fed on the wheat plants until mummies appeared. Both the aphid and parasitoid colonies were maintained at suitable environmental conditions (25 ± 1ºC, 70 ± 5% RH and 16:8 h L:D photoperiod). In addition, a cotton ball soaked with 25% honey solution was provided in the cylindrical plastic cage as food for adult parasitoids (Wäckers, 2003).

Demographic parameters

To investigate the demographic parameters of *D. rapae*, the wheat seedlings were initially infested with 50 second instar nymphs of *S. graminum*, the preferred host stage for the parasitoid (Jokar et al, 2012) placed into 1.5 ml micro tube inside a BD Falcon^{tm} 50 ml conical centrifuge tube, and exposed to a pair of *D. rapae*. After a 24 h exposure, the parasitoids were removed, and the exposed aphids were maintained under constant environmental conditions until mummies appeared. Each mummified aphid was separately placed into a 5 ml sample tube. The lids of sample tubes were covered with fine nylon mesh to allow adequate ventilation. The mummies were checked daily until adult parasitoids emerged. The number and sex of emerged adult wasps were recorded. Upon the emergence, naïve (without prior mating or oviposition experience) and one-day-old adult parasitoids were collected and used for the test of life-time fecundity. Also, a pair of one-day-old *D. rapae* was exposed daily to wheat leaves infested with 50 second instar nymphs of the host aphid as described above. The parasitoids were transferred to a new Falcon with a fresh group of 50 second instar nymphs of the host aphids after each day exposure until the female died. If the male died before the female, an alternative male that had been maintained in the same stock culture was introduced. The exposed aphids were maintained under the same experimental conditions until mummies appeared. The numbers of mummies were recorded and was used to approximately estimate the initial number of laid eggs by each female parasitoid. In all experiments, adults of *D. rapae* were fed on a 25% honey solution streaked on the inside wall of each container. These experiments were similarly performed at five constant temperatures of 10, 15, 20, 25 and 27.5 °C, relative humidity of 70 ± 5% and a photoperiod of 16L: 8D h. In addition, the temperature of 30 °C was examined but no adult wasps emerged at this temperature; hence, the demographic parameters could not be estimated for 30 °C.

Statistical analysis

Data from all individuals of parasitoids from different temperatures were subjected to a female age-specific life table procedure. By using the fertility and survivorship schedules, the life table and reproduction parameters were determined according to the formula suggested by Carey (1993, 2001). The jackknife procedure was used to calculate the pseudo-values of life history parameters in order to compare them statistically (Maia, Luiz, & Campanhola, 2000). Data were tested for normality with Kolmogorov-Smirnov test before they were subjected to ANOVA. Data concerning immature development, adult longevity, life span, reproduction, and life table parameters were compared using one-way ANOVA. If significant differences were determined, multiple comparisons were made using Tukey's honestly significant difference test ($P < 0.05$). All statistical analyses were carried out using SAS software (SAS Institute, 2003).

RESULTS

Development time and fecundity

The mean immature development, adult longevity, and life span of *D. rapae* at different temperatures are summarized in Table 1. The parasitoid completed its development at all five evaluated temperatures. The immature development period (egg to adult) significantly decreased with increasing temperatures from 10 to 25 °C and increased at 27.5 °C (df = 4, 496; F = 65.89; P < 0.001). The immature development periods of *D. rapae* were significantly longer at 10 °C (25.49 days) and shorter at 25 °C (9.24 days), respectively. Both adult longevity (df = 4, 160; F = 36.67; P < 0.001) and life span (df = 4, 160; F = 12.64; P < 0.001) were significantly affected by the temperatures. The adult longevity (20.44 days) and life span (45.93 days) were significantly longer at 10 °C. Moreover, the temperatures of 27.5 and 25 °C showed the shortest adult longevity (2.87 days) and life span (12.80 days), respectively.

The effect of temperature was highly significant for the different reproductive parameters including mean number of mummified aphids per female (df = 4, 153; F = 25.69; P < 0.0001), mean number of adults emerged per female (df = 4, 140; F = 15.20; P < 0.01), and mean number of adults emerged per female per day (df = 4, 153; F = 235.12; P < 0.0001). The parasitoid showed the highest value of mummified aphids per female at 20 °C (120.08) and the lowest value was found at 27.5 °C (12.24). There were no significant differences between the numbers of mummified aphids per female and adults emerged per female at 10 °C, 15 °C and 20 °C. Similarly, the maximum and minimum values of adults emerged per female were recorded at 20 °C (105.29) and 27.7 °C (9.46), respectively. Also, the maximum and minimum values of mean fertile eggs per day were estimated to be 17.10 and 3.25 at 25 and 10 °C, respectively (Table 2).

Table 1. Immature development, adult longevity, and life span (days ± SE) of *Diaeretiella rapae* reared on *Schizaphis graminum* at five constant temperatures.

Parameters	Temperature (°C)				
	10	15	20	25	27.5
Immature development	25.49 ± 0.09a*	22.09 ± 0.10b	17.64 ± 0.05c	9.24 ± 0.05e	11.95 ± 0.21d
Adult longevity	20.44 ± 0.38a	17.41 ± 0.34b	10.11 ± 0.30c	4.05 ± 0.16d	2.87 ± 0.30e
Life span	45.93 ± 0.36a	39.17 ± 0.46b	27.53 ± 0.36c	12.80 ± 0.26e	14.91 ± 0.25d

***Values followed by the same letter within each row are not significantly different at P < 0.05 (Tukey's HSD multiple range test).

Table 2. The reproduction parameters (mean ± SE) of *Diaeretiella rapae* reared on *Schizaphis graminum* at five constant temperatures.

Parameters	Temperature (°C)				
	10	15	20	25	27.5
Mummified aphids per female	69.10 ± 1.59[c*]	101.97 ± 2.63[b]	120.08 ± 1.97[a]	67.24 ± 2.37[c]	12.24 ± 0.52[d]
Adults emerged per female	62.11 ± 1.05[c]	96.43 ± 2.80[b]	105.29 ± 1.39[a]	54.79 ± 2.10[d]	9.46 ± 0.31[e]
Adults emerged per female per day	3.25 ± 0.07[d]	5.66 ± 0.15[c]	11.34 ± 0.19[b]	17.10 ± 0.56[a]	3.91 ± 0.16[e]

***Values followed by the same letter within each row are not significantly different at P < 0.05 (Tukey's HSD multiple range test).

Survival rate and life expectancy

The age-specific survival rate pattern of *D. rapae* at different temperatures is shown in Fig. 1. *Diaeretiella rapae* completed its developmental from 10 to 27.5°C. The curves of age-specific survival rate (l_x) show the probability that a newly laid egg will survive to age *x*. The survival rate of *D. rapae* at various temperatures was different. The survival rate decreased when temperatures increased from 10 to 25 °C. The nearly similar pattern was observed for survival rate at 25 and 27.5 °C. The longest survival rate (52 days) occurred at 10°C and its shortest value (17 days) was observed at 25 and 27.5 °C (Fig. 1). The life expectancy (e_x) of newly laid eggs of *D. rapae* was 44.07, 38.28, 26.14, 12.59, and 13.82 days at 10, 15, 20, 25 and, 27.5 °C, respectively, which is decreased with increasing age (Fig. 2). The oviposition started after 25, 21, 16, 8, and 10 days at the mentioned temperatures, respectively (Fig. 3). According to our results, the highest value of age-specific fecundity at 10, 15, 20, 25 and, 27.5 °C was 6.61, 11.27, 20.33, 18.04, and 3.00 at the age of 30, 26, 19, 10, and 11 days, respectively.

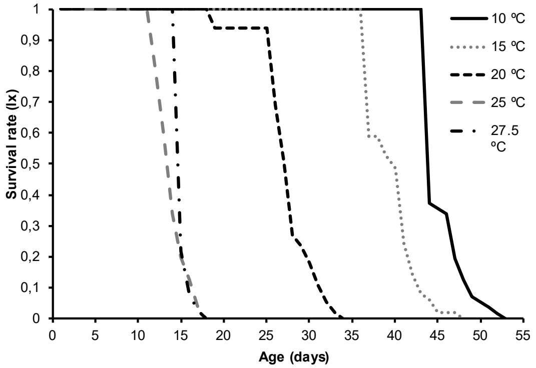

Figure 1. Age-specific survival rate (l_x) of *Diaeretiella rapae* reared on *Schizaphis graminum* at five constant temperatures.

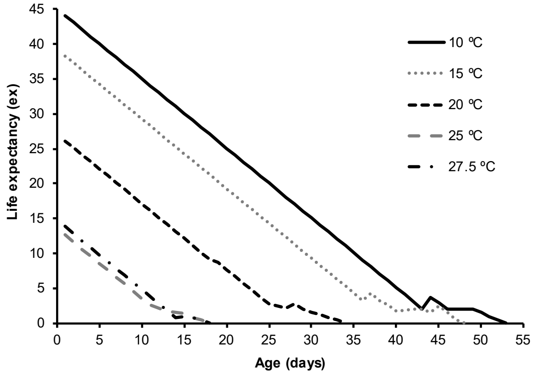

Figure 2. Life expectancy (e_x) of *Diaeretiella rapae* reared on *Schizaphis graminum* at five constant temperatures.

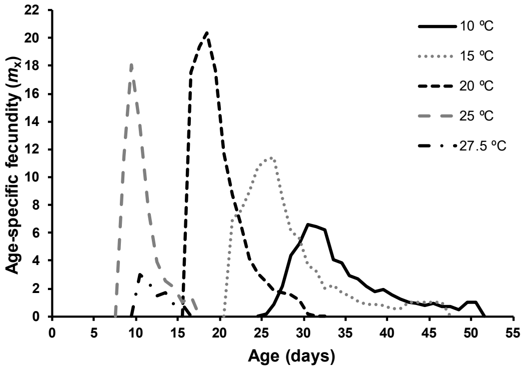

Figure 3. Age-specific fecundity (m_x) of *Diaeretiella rapae* reared on *Schizaphis graminum* at five constant temperatures.

Population growth parameters

The population growth parameters of *D. rapae* at five constant temperatures are summarized in Table 3. The net reproductive rate (R_0) is the average number of female offspring produced in a lifetime by a female and was significantly different at various temperatures (df = 4, 155; F = 20.13; P < 0.01) according to the pattern 20> 15> 25> 10> 27.5 °C. The mean values of R_0 ranged from 52.39 female offspring/female at 25 °C to 0.77 female offspring/female at 27.5 °C. The intrinsic rate of increase (r) was also significantly different at various constant temperatures (df = 4, 155; F = 25.97; P < 0.01), with the highest value (0.374 day^{-1}) at 25 °C and the lowest (0.019 day^{-1}) at 27.5 °C. Similarly, the finite rate of increase (λ) was significantly different among treatments (df = 4, 155; F = 44.54; P < 0.01). The mean values of finite rate of increase ranged from 1.453 to 0.981 day^{-1} at 25 and 27.5 °C, respectively. Also, the temperature showed significantly effects on the doubling time (DT) (df = 4, 155; F = 27.79; P < 0.01), and mean generation time (T) (df = 4, 155; F = 16.14; P < 0.01). The doubling time and mean generation time were significantly lower at 25 ° C (1.85 and 7.73 days, respectively).

Table 3. Population growth parameters (mean ± SE) of *Diaeretiella rapae* reared on *Schizaphis graminum* at five constant temperatures.

Parameters	Temperature (°C)				
	10	15	20	25	27.5
Gross reproduction rate (GRR)	38.68 ± 0.89^{d*}	50.08 ± 1.35^{c}	66.46 ± 1.24^{a}	57.69 ± 1.27^{b}	9.48 ± 0.42^{e}
Net reproduction rate (R_0; ♀♀/♀)	14.16 ± 0.39^{d}	24.75 ± 0.96^{b}	52.39 ± 0.85^{a}	16.92 ± 0.80^{c}	0.77 ± 0.05^{e}
Intrinsic rate of increase (r, day^{-1})	0.096 ± 0.001^{d}	0.150 ± 0.001^{c}	0.247 ± 0.001^{b}	0.374 ± 0.004^{a}	0.019 ± 0.009^{e}
Finite rate of increase (λ; day^{-1})	1.101 ± 0.001^{d}	1.160 ± 0.001^{c}	1.281 ± 0.001^{b}	1.453 ± 0.006^{a}	0.981 ± 0.005^{e}
Doubling time (DT; days)	7.21 ± 0.08^{a}	4.66 ± 0.04^{b}	2.81 ± 0.01^{c}	1.85 ± 0.22^{d}	7.37 ± 0.52^{a}
Mean generation time (T; days)	27.58 ± 0.16^{a}	21.74 ± 0.10^{b}	15.95 ± 0.62^{c}	7.73 ± 0.06^{e}	13.86 ± 0.11^{d}

* Values followed by the same letter within each row are not significantly different at P < 0.05 (Tukey's HSD multiple range test).

DISCUSSION

Although insects do not live in a constant environmental condition without temperature fluctuation, the results of studies under stable temperatures can provide a valuable insight into the understanding the population dynamics of various insects (Haghani et al, 2007; Amiri et al, 2010; Zamani, Haghani, & Kheradmand, 2012; Rezaei et al, 2020b). This study provides the biological response of *D. rapae* on *S. graminum* cultured on wheat plant to a broad range of constant temperatures, which has not been previously reported. Our findings revealed that temperature had a strong effect on the reproductive and demographic parameters of *D. rapae*. The parasitoid was able to develop across a wide range of temperatures from 10 to 27.5 °C, while the reared parasitoids did not survive and develop at 30 °C. This is in agreement with other studies in which the lethal maximum temperature (T_{max}) of *D. rapae* was estimated from Briere-1 and Lactin-1 Models to be 31.5 and 31.94 °C, respectively (Bernel & Gonzalez, 1993; Tazerouni et al, 2012; Kazemi et al, 2020).

Demographic parameters are important in measurement of population growth capacity of an insect species and they may depend on several factors, in particular temperature (Ismail et al, 2014; Tazerouni et al, 2012; Rezaei et al, 2020a). Many studies have assessed the demographic parameters of parasitoids at various constant temperatures (e.g., Bernal & Gonzalez, 1997; Amiri et al, 2010; Tazerouni et al, 2013; Rezaei et al, 2020a). In the current study, temperature had a significant influence on all measured reproductive and demographic parameters. The intrinsic rate of increase (*r*) is the most important parameter indicating the most favorable temperature for population growth and reflects overall effects of temperature on development, reproduction, and survival (Carey, 1993, 2001; Amiri et al, 2010). The estimated values of *r* in all examined temperatures were positive, indicating that the parasitoid can fully development and reproduction in these temperatures. This is consistent with studies in which *D. rapae* was reared on *D. noxia* (Tazerouni et al, 2012), *L. erysimi*, *B. brassicae*, and *M. persicae* (Karami et al, 2018; Nisar & Rizvi, 2020). The greatest value of *r* was obtained at 25 °C (0.374 day^{-1}), indicating the optimum temperature for this parasitoid reproduction. Moreover, the temperature of 20 °C showed the highest values of mummified aphids and adults emerged per female (120.08 and 105.29, respectively). To date, some studies have reported the intrinsic rate of increase of *D. rapae* at different conditions (Bernal & González, 1997; Tazerouni et al, 2012; Karami et al, 2018; Nisar & Rizvi, 2021). For instance, Ghorbanian et al (2019) reported that the intrinsic rate of increase of *D. rapae* on *M. persicae* established on different cultivars of pepper at 25 °C ranged from 0.279 to 0.389 day^{-1}. In contrast to the current results, Tazerouni et al (2013) showed that *D. rapae* could potentially control *D. noxia* at a temperature range of 10 to 15 °C. They obtained the highest R_0 and *r* for *D. rapae* at 10 °C (22.99) and 20 °C (0.189 day^{-1}), respectively. Also, the *r* value of *D. rapae* on *D. noxia* at 26.7 °C was calculated as 0.202 day^{-1} (Bernal & Gonzalez, 1997). A possible explanation for these differences may be related to host aphid species, as previously reported for the performance of *D. rapae* on different host species (Silva et al, 2011; Souza et al, 2017; Nisar & Rizvi, 2021). The higher value of *r* in the current study indicated that *S. graminum* is a more suitable host than *D. noxia* for the parasitoid. However, the *r* value could be affected by various factors such as host plant (Karami et al, 2018; Ghorbanian et al, 2019), host and parasitoid size (Jervis & Kidd, 1996), and geographic populations of parasitoid (Hayakawa et al, 1990), among other experimental conditions. Moreover, it is mentioned that the intrinsic rate of increase is indicative of population growth only if the population has reached a stable age structure (Carey, 1993). Hence, it is suggested to use the emergence rate, net reproduction rate, and cumulative fecundity curves of the first generation, which are desirable for practical use in biological control program (Ismail et al, 2014; Rezaei et al, 2020a).

The highest net reproductive rate (R_0) occurred at 20 °C (52.39 female offspring/female), which is different from the findings reported by Tazerouni et al (2012) and Bernal & Gonzalez (1997) for *D. rapae* on *D. noxia*. These differences can be explained by the variation in the aphid and host plant species. The lowest R_0 at 27.5 °C (0.77 female offspring/female) resulted in high mortality of the immature life stages or adults from emergence to oviposition peak (Fig. 1). The shortest mean generation time was obtained at 25 °C (7.73 days) indicating that *D. rapae* developed faster at this temperature than the others.

The fecundity rate of a natural enemy is also the important factors to determine its effectiveness (Tazerouni et al, 2012; Zamani et al, 2012). In the present study, the highest value of mummified aphids per female was observed at 20 °C (120.08). In contrast to earlier findings, the reported fecundity rate of *D. rapae* on *D. noxia* at 21.1 °C was 50.20 (Bernal & Gonzalez, 1997). In addition, Nisar & Rizvi (2021) reported that the potential fecundity of *D. rapae* on *L. erysimi*, *M. persicae*, and *B. brassicae* at 26 °C were 101.52, 105.46, and 92.36, respectively. This inconsistency may be due to differences in host aphid species, geographic populations of the parasitoid, and genetic difference as a result of laboratory rearing (Silva et al, 2011; Nisar & Rizvi, 2020).

Several models are used to predict the population dynamics of pest and natural enemies (e.g., Lotka-Volterra model, Nicholson-Baily model, etc), and the intrinsic rate of increase is a key parameter in nearly all of these models (Mirhosseini, Fathipour, & Reddy, 2017). In many cases, the intrinsic rate of increase has been evaluated at a constant environmental condition while the natural enemies are faced with temperature fluctuations in the field and their population growth rate is different at the various temperatures (Amiri et al, 2010; Kant, Minor, & Trewick, 2012). In the present study, the intrinsic rate of increase of *D. rapae* was calculated at different constant temperatures. Hence, it is more helpful to precisely predict population dynamics of *D. rapae* in the field under variable conditions. However, an understanding of thermal requirements of a particular natural enemy (e.g. *D. rapae*) is important for predicting of its potential geographic distribution in different regions. Using the current results, we will able to generate isothermal lines to predict the probable distribution regions for *D. rapae* (Hayakawa et al, 1990; Haghani et al, 2007; Amiri et al, 2010).

The current study shows that the temperature range of 20 to 25 °C may be the best choice for maintenance of a laboratory colony of *D. rapae* on *S. graminum*. In accordance, Basheer et al (2014) revealed that the optimum temperature for *D. rapae* on *B. brassicae* is 20 to 25 °C. Based on the temperature-dependent functional response, the mentioned temperature range was optimized for rearing of *D. rapae* on *S. graminum* (Talebi et al, 2022). Similarly, this temperature range is also optimum for fecundity and fertility rates of *Aphidius matricariae* Haliday and *Aphidius colemani* Viereck (both Hymenoptera: Braconidae) (Zamani et al, 2012). It is important to mention that 26 °C is optimal temperature for *S. graminum* development and growth (Tofangsazi, Kheradmand, Shahrokhi, & Talebi, 2010). Therefore, *D. rapae* could be considered as a good candidate for biological control of *S. graminum* in wheat field at the beginning of spring and autumn before the population of the aphid is built (Tazerouni et al, 2013). Moreover, Kant et al (2012) stated that pre-release of *D. rapae* for suppression of early population of *M. persicae* is required for effective biological control.

CONCLUSIONS

In conclusion, this research confirmed that the *D. rapae* could develop from egg to adult and reproduce successfully within a temperature range of 10 - 27.5 °C. Our laboratory results suggest that the range of 20 to 25 °C is the most suitable temperature regimes for *D. rapae* population growth on *S. graminum*. However, the intrinsic rate of increase (r) was significantly greater at 25 °C compared to other temperatures, which suggest that this is the most suitable temperature for the control of *S. graminum.* Further consideration in semi-field and field applications would help to obtain more reliable results and understanding. In addition, using a temperature-controlled environment is a vital component of mass rearing facilities for consistent rearing of *D. rapae* for biological control of aphids. Thus, the results can be used in mass rearing and mass release programs of *D. rapae*.

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REFERENCES

Amiri, A., Talebi, A.A., Zamani, A.A., & Kamali, K. (2010). Effect of temperature on demographic parameters of the hawthorn red midget moth, *Phyllonorycter corylifoliella*, on apple. *Journal of Insect Science*, 10(1),1-12.

Basheer, A., Aslan, L., & Asaad, R. (2014). Effect of constant temperatures on the development of the aphid parasitoid species, *Diaeretiella rapae* (M'Intosh) (Hymenoptera: Aphidiidae). *Egyptian Journal of Biological Pest Control*, 24(1),1-5.

Bernal, J. & Gonzalez, D. (1993). Temperature requirements of four parasites of the Russian wheat aphid *Diuraphis noxia*. *Entomologia Experimentalis et Applicata*, 69(2), 173-182.

Bernal, J. & Gonzalez, D. (1997). Reproduction of *Diaeretiella rapae* on Russian wheat aphid hosts at different temperatures. *Entomologia Experimentalis et Applicata*, 82(2),159-166.

Blackman, R.L. & Eastop, V.F. (2006). *Aphids on the world's herbaceous plants and shrubs*. John Wiley & Sons, USA.

Bodlah, I., Naeem, M., & Mohsin, A.U. (2012). Distribution, hosts and biology of *Diaeretiella rapae* (M'Intosh) (Hymenoptera: Braconidae: Aphidiinae) in Punjab, Pakistan. *Pakistan Journal of Zoology*, 44(5),1307-1315.

Boivin, G., Hance, T., & Brodeur, J. (2012). Aphid parasitoids in biological control. *Canadian Journal of Plant Science*, 92,1-12.

Carey, J.R. (1993). *Applied demography for biologists*. Oxford University Press, New York.

Carey, J.R. (2001). Insect biodemography. *Annual Review of Entomology*, 46,79-110.

Farahani, S., Talebi, A.A. & Rakhshani, E. (2016). Iranian Braconidae (Insecta: Hymenoptera: Ichneumonoidea): diversity, distribution and host association. *Journal of Insect Biodiversity and Systematics*, 2(1),1-92.

Ghorbanian, M., Fathipour, Y., Talebi, A.A., & Reddy, G.V. (2019). Different pepper cultivars affect performance of second (*Myzus persicae*) and third (*Diaeretiella rapae*) trophic levels. *Journal of Asia-Pacific Entomology*, 22(1),194-202.

Haghani, M., Fathipour, Y., Talebi, A.A., & Baniameri, V. (2007). Temperature-dependent development of *Diglyphus isaea* (Hymenoptera: Eulophidae) on *Liriomyza sativae* (Diptera: Agromyzidae) on cucumber. *Journal of Pest Science*, 80(2),71-77.

Hayakawa, D.L., Grafius, E., & Stehr, F.W. (1990). Effects of temperature on longevity, reproduction, and development of the asparagus aphid (Homoptera: Aphididae) and the parasitoid, *Diaeretiella rapae* (Hymenoptera: Braconidae). *Environmental Entomology*, 19(4),890-897.

Ismail, M., Van Baaren, J., Briand, V., Pierre, J. S., Vernon, P., & Hance, T. (2014). Fitness consequences of low temperature storage of *Aphidius ervi*. *BioControl*, 59(2), 139-148.

Jervis, M. & Kidd, N. (1996). *Insect Natural enemies, Practical approaches to their study and evaluation*. Springer Netherlands.

Jokar, M., Zarabi, M., Shahrokhi, S., & Rezapanah, M. (2012). Host-stage preference and functional response of aphid parasitoid *Diaeretiella rapae* (McIntosh) (Hym.: Braconidae) on greenbug, *Schizaphis graminum* (Rondani) (Hem: Aphididae). *Archives of Phytopathology and Plant Protection*, 45(18), 2223-2235.

Kant, R., Minor, M.A., & Trewick, S.A. (2012). Reproductive strategies of *Diaeretiella rapae* (Hymenoptera: Aphidiinae) during fluctuating temperatures of spring season in New Zealand. *Biocontrol Science and Technology*, 22(1), 1-9.

Karami, A., Fathipour, Y., Talebi, A.A., & Reddy, G.V. (2018). Parasitism capacity and searching efficiency of *Diaeretiella rapae* parasitizing *Brevicoryne brassicae* on susceptible and resistant canola cultivars. *Journal of Asia-Pacific Entomology*, 21(4),1095-1101.

Karimi-Malati, A., Fathipour, Y., Talebi, A.A., & Bazoubandi, M. (2014). Life table parameters and survivorship of *Spodoptera exigua* (Lepidoptera: Noctuidae) at constant temperatures. *Environmental Entomology*, 43(3),795-803.

Kazemi, M., Talebi, A.A., Tazerouni, Z., Fathipour, Y., Rezaei, M., & Mehrabadi, M. (2020). Thermal requirements of parasitoid wasp, *Diaretiella rapae* (Hym.: Braconidae) reared on *Schizaphis graminum* (Hem.: Aphididae) under laboratory conditions. *Journal of Plant Pest Research*, 10(2),1-13.

Maia, A.D.H., Luiz, A.J., & Campanhola, C. (2000). Statistical inference on associated fertility life table parameters using jackknife technique: computational aspects. *Journal of Economic Entomology*, 93(2),511-518.

Mirhosseini, M. A., Fathipour, Y., & Reddy, G.V. (2017). Arthropod development's response to temperature: a review and new software for modeling. *Annals of the Entomological Society of America*, 110(6), 507-520.

Nisar, S. & Rizvi, P.Q. (2021). Host fitness of different aphid species for *Diaeretiella rapae* (M'Intosh): a life table approach. *International Journal of Tropical Insect Science*, 41, 787-799.

Rakhshani, E., Tomanovic, Z., Starý, P., Talebi, A.A., Kavallieratos, N.G., Zamani, A.A., & Stamenkovic, S. (2008). Distribution and diversity of wheat aphid parasitoids (Hymenoptera: Braconidae: Aphidiinae) in Iran. *European Journal of Entomology*, 105, 863-870.

Rezaei, M. & Moharramipour, S. (2019). Efficacy of Dayabon, a botanical pesticide, on different life stages of *Myzus persicae* and its biological control agent, *Aphidius matricariae*. *Journal of Crop Protection*, 8, 1-10.

Rezaei, M., Talebi, A.A., Fathipour, Y., Karimzadeh, J., Mehrabadi, M., & Reddy, G.V.P. (2020a). Effects of cold storage on life-history traits of *Aphidius matricariae*. *Entomologia Experimentalis et Applicata*, 168, 800-807.

Rezaei, M., Talebi, A.A., Fathipour, Y., Karimzadeh, J., Mehrabadi, M., & Dindo, M.L. (2020b). Effects of constant low-temperature storage on the performance of a commercial strain of *Aphidius colemani*. *Bulletin of Insectology*, 73(1),125-135.

SAS Institute (2003). GLM: a guide to statistical and data analysis, version 9.1. SAS institue, Cary, NC, USA.

Silva, R.J., Cividanes, F.J., Pedroso, E.C., & Sala, S.R.D. (2011). Host quality of different aphid species for rearing *Diaeretiella rapae* (McIntosh) (Hymenoptera: Braconidae). *Neotropical Entomology*, 40(4), 477-482.

Singh, R. & Singh, G. (2015). Systematics, distribution and host range of *Diaeretiella rapae* (McIntosh) (Hymenoptera: Braconidae, Aphidiinae). *International Journal of Research Studies in Biosciences*, 3(1), 1-36.

Soni, S. & Kumar, S. (2021). Biological and behavioural characteristics of *Diaeretiella rapae* (McIntosh), a parasitoid of *Lipaphis erysimi* (Kaltenbach) infesting oilseed brassicas in India. *Biocontrol Science and Technology*, 31(4), 400-417.

Souza, M.F., Veloso, L.F.A., Sampaio, M.V., & Davis, J.A. (2017). Influence of host quality and temperature on the biology of *Diaeretiella rapae* (Hymenoptera: Braconidae, Aphidiinae). *Environmental Entomology*, 46(4), 995-1004.

Talebi, A.A., Kazemi, M., Rezaei, M., Mirhosseini, M.A., & Moharramipour, S. (2022). Host stage preference and temperature-dependent functional response of *Diaeretiella rapae* (Hymenoptera: Braconidae) on *Schizaphis graminum* (Hemiptera: Aphididae). *International Journal of Tropical Insect Science*, 42(1), 415-424.

Tazerouni, Z., Talebi, A.A.; & Rakhshani, E. (2012). Comparison of development and demographic parameters of *Diuraphis noxia* (Hem., Aphididae) and its parasitoid, *Diaeretiella rapae* (Hym., Braconidae: Aphidiinae). *Archives of Phytopathology and Plant Protection*, 45(8), 886-897.

Tazerouni, Z., Talebi, A.A., Rakhshani, E., & Zamani, A.A. (2013). Comparison of life table parameters of Russian wheat aphid, *Diuraphis noxia*, and its parasitoid, *Diaeretiella rapae* under constant temperatures. *Applied Entomology and Phytopathology*, 81,1-10.

Tofangsazi, N., Kheradmand, K., Shahrokhi, S., & Talebi, A.A. (2011). Demography of greenbug, *Schizaphis graminum* (Rondani) (Hemiptera: Aphididae) on six barley cultivars. *Archives of Phytopathology and Plant Protection*, 44, 484-492.

Tofangsazi, N., Kheradmand, K., Shahrokhi, S. & Talebi, A.A. (2010). Temperature-dependent life history of *Schizaphis graminum* on barley. *Bulletin of Insectology*, 63(1),79-84.

van Emden, H.F. & Harrington, R. (2007). *Aphids as crop pests*. CABI, CPI Group Ltd, Croydon, UK.

Wäckers, F.L. (2003). Quality control and production of biological control agents: theory and testing procedures. In J.C., van Lenteren (Ed.). *The parasitoids' needs for sweets: sugar in mass rearing and biological control* (pp. 59-72). CABI Publishing, Wallingford, UK.

Zamani, A.A., Haghani, M., & Kheradmand, K. (2012). Effect of temperature on reproductive parameters of *Aphidius colemani* and *Aphidius matricariae* (Hymenoptera: Braconidae) on *Aphis gossypii* (Hemiptera: Aphididae) in laboratory conditions. *Journal of Crop Protection*, 1(1), 35-40.

Zogli, P., Alvarez, S., Naldrett, M.J., Palmer, N.A., Koch, K.G., Pingault, L., Bradshaw, J.D., Twigg, P., Heng-Moss, T.M., Louis, J., & Sarath, G. (2020). Greenbug (*Schizaphis graminum*) herbivory significantly impacts protein and phosphorylation abundance in switchgrass (*Panicum virgatum*). *Scientific Reports*, 10(1), 1-15.