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RESEARCH ARTICLE

Effect of temperature and relative humidity on some biological traits of two *Trichogramma cacoeciae* (Marchal) (Hymenoptera: Trichogrammatidae) strains

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Temperature and relative humidity are key factors affecting the physiological and behavioural responses of natural enemies, including *Trichogramma* parasitoids frequently employed as biological control agents. Here, the effect of three temperatures (25, 30 and 35 °C) and relative humidity levels (10, 75 and 100%) on the fitness of two *Trichogramma cacoeciae* (Marchal) strains (Tunisian/Italian) were evaluated. Results indicated that temperature and relative humidity influenced all life-history parameters of parasitoids. Parasitism of the G0 generation by the Tunisian strain was higher compared to that of the Italian strain at 30 °C (10% RH) (22.33 ± 5.94 and 16.46 ± 6.45, respectively, for the Tunisian and Italian strain) and 35 °C (75% RH) (16.26 ± 5.11 and 11.33 ± 5.81, respectively, for the Tunisian and Italian strain). Furthermore, the parasitism rate is better in the G1 compared to the G0 generation only for the Italian strain at 25–30 °C and at 10, 75 and 100% RH. Emergence was significantly decreased for both strains at 35 °C regardless of the relative humidity level. For the G1 generation, no parasitism and emergence were shown by the Italian strain at 35 °C for all tested relative humidities. Our data indicate the Tunisian strain is adapted to higher temperatures. The implications of these results to improve the biological control of lepidopteran pests are discussed.

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INTRODUCTION

Egg parasitoids of the genus *Trichogramma* (Hymenoptera: Trichogrammatidae) are widely used for biological control of major lepidopteran pests worldwide (Smith 1996; Mills 2009; Cherif et al. 2021). These wasps, characterised by their small size (ranging from 0.2 to 1.5 mm), comprise about 800 species belonging to 90 genera (Jalali et al. 2016). More than 200 of these *Trichogramma* species are used for innundative releases to control a wide range of insect pests (Wajnberg and Hassan 1994; Smith 1996; Mills 2009; Querino et al. 2009; Iqbal et al. 2020; Yuan et al. 2012). In Tunisia, select *Trichogramma* species, especially the indigenous species *T. cacoeciae* (Marchal), are known to have populations with specific biological features adopted to the climatic conditions of their different areas of origin (Pizzol et al. 2010), and have been successfully tested against some lepidopteran pests of economic importance including *Tuta absoluta* (Meyrick) (Gelechiidae) and *Ectomyelois ceratoniae* (Zeller) (Pyralidae) (Cherif et al. 2019; Zougari et al. 2020; Hached et al. 2021; Alloui-Griza et al. 2022).

The broad success of *Trichogramma* releases against economic pests is related mainly to their easy rearing on alternative hosts and compatibility with other management strategies (Smith 1996; Mills 2009; Querino et al. 2009; Iqbal et al. 2020; Cherif et al. 2021). Various factors may influence the development of *Trichogramma* species/strains as successful biocontrol agents (Nagaraja 2013; del Pino et al. 2020). For example, changes in climatic conditions may affect the physiology and behaviour of *Trichogramma* parasitoids in the field. In some cases, their distribution may be altered which may affect their phenological synchrony with their hosts and/or may disrupt multitrophic interactions (Thomson et al. 2010; Tougeron et al. 2020). Moreover, some biological aspects of *Trichogramma* species such as emergence and parasitism rates and the longevity of the progeny may be affected by changes in temperature and relative humidity (RH) (Nagaraja 2013; del Pino et al. 2020; Cherif et al. 2021). Also, strains (a genetic variant of a given species) may influence the performance of *Trichogramma* wasps in the field (Smith 1996; Pizzol et al. 2010; Vyas-Patel and Mumford 2018).

Little information is available about the impact of abiotic factors, especially relative humidity, on the fitness of different strains of *T. cacoeciae*. This work aimed to study the combined effect of various temperature and relative humidity levels on two strains of *T. cacoeciae*, one originating from Italy and the other from Tunisia, under laboratory conditions.

MATERIALS AND METHODS

Insects

Two strains (Tunisian and Italian) of *Trichogramma cacoeciae* were used in this study. The Tunisian strain was provided by the National Agronomic Institute of Tunisia (Tunisia), while the Italian one was obtained from the Catholic University of Louvain (Belgium). The two strains were reared following the same rearing condition using ultratviolet-irradiated eggs of the alternative host *Ephestia kuehniella* (Zeller) (Lepidoptera: Pyralidae) maintained on wheat bran diet, at 25 °C, RH 75–80% and a 14:10 L: D photoperiod in climate-controlled rooms. *E. kuehniella* eggs (approximately 300 unparasitised eggs) were glued onto paper card (1 × 5 cm^2) and offered to newly emerged *Trichogramma* wasps (approximately 15 females) in plastic tubes (2.5 × 8.5 cm^2). Parasitoids were fed with honey droplets placed into the inner wall of the tubes. Egg cards were replaced daily with fresh ones until parasitoids death. Cards with parasitised (=blackened) eggs were incubated in a climatic controlled chamber under the same conditions described above.

Experiment

A single one-day-old *Trichogramma* female of each strain was exposed to 50 unparasitised fresh host eggs glued on a small paper card and incubated for 24h at three different temperature regimes (25, 30 and 35 °C) in conjunction with varying relative humidity levels (10, 75 and 100%). The different humidity levels were applied consistently across all three temperature settings during the experiment. Fifteen females per strain were used for each temperature and relative humidity regimes. Relative humidity was adjusted using plastic boxes containing saturated salt solution composed of sodium hydroxide for 10% RH, sodium chloride for 75% RH and sodium sulphate anhydrous for 100% RH (Hodgman 1948). Humidity levels were checked frequently, and adjustments were made if needed. One incubator (Binder GmbH, KBW 240 (E5.1), Tuttlingen, Germany) with a thermal precision of ± 1 °C, and a photoperiod of 14L: 10D was used for each temperature. Fifteen newly emerged females of G0 generation were chosen at random and incubated at the three temperature and relative humidity regimes already described. Parasitism and emergence rates (%) were measured for each treatment corresponding to both generations (G0 and G1). The number of parasitised eggs and emerged wasps was calculated by counting the number of blackened eggs and emergence holes respectively.

Statistical analysis

The software SPSS 21 (SPSS Inc. 2012) was used to perform all statistical analysis. Obtained data were log (x+1) transformed before analysis to stabilize the variance (Sokal and Rohlf 1981). A generalised linear model (GLM) was carried out to test: firstly, the effect of temperature, relative humidity and strain as well their interactions on parasitism and adult emergence of two strains (Italian *vs* Tunisian) of *T. cacoeciae* parasitoids; and secondly, the effect of temperature, relative humidity and generation, as well their interactions, on parasitism and adult emergence of two *T. cacoeciae* strains. One-way ANOVA was then carried out to test the effect of the three temperature regimes (25, 30 and 35 °C) on the parasitism or the emergence for each *Trichogramma* strain (Tunisian or Italian) separately for each relative humidity level (10%, 75% and 100%). We also analysed, using one-way ANOVA, differences of parasitism or emergence between the two *Trichogramma* strains for each temperature and relative humidity level. Means were separated using Duncan's multiple range post-hoc test at $p < 0.05$.

RESULTS

G0 generation

Results indicated that only the interaction of temperature, relative humidity and strain had a significant effect on the number of parasitised eggs (Table 1). Also, our data demonstrated that both temperature and relative humidity (RH), but not their interaction, affected the parasitism rate of the G0 generation (Table 1). Similarly, strain significantly affected the number of parasitised eggs (Table 1). Results related to the effect of temperature, relative humidity, strain and their interactions on the number of parasitised eggs are provide in Table 2. At 10% RH and 75% RH, a significant difference was observed between the two strains only at 30 or 35 °C respectively (Table 2). Furthermore, a significant difference was shown between the three tested temperatures separately for the Italian and Tunisian strains at the aforementioned RH (Table 2). A decrease in the number of parasitised eggs was clearly recorded at 35 °C for all tested relative humidities (Table 2). At 100% RH, no significant difference was recorded between the two tested strains for each studied temperature ($F_{1,29} = 0.00$, $p = 0.95$ at 25 °C; $F_{1,29} = 0.59$, $p = 0.44$ at 30 °C; $F_{1,29} = 0.66$, $p = 0.42$ at 35 °C). However, a significant difference was indicated between the three tested temperature separately for each strain (Table 2).

The emergence rates of adults were significantly influenced by temperature, relative humidity and strain; no significant difference was shown for their interaction (Table 3). A significant decrease in the progeny was obtained at high temperature level (35 °C) regardless of the relative humidity. For example, at 10% RH, the number of emerged adults was 0.46 ± 1.08 compared to 2.80 ± 1.55 respectively for Italian and Tunisian strains of *T. cacoeciae* (Figure 1). The number of emerged adults differed significantly between the two strains at the three tested temperatures only for 10% RH ($p < 0.05$) and 100% RH ($p < 0.05$) (Figure 1). At 75% RH, a significant difference was shown only for 35 °C ($p < 0.05$) (Figure 1). A significant difference was shown between the three tested temperature for each strain at 10% RH ($p < 0.05$), 75% RH ($p < 0.05$) and 100% RH ($p < 0.05$) (Figure 1).

G1 generation

Temperature, RH, and strain had a significant effect on the parasitism rates of the G1 generation (Table 1). Only the interaction of temperature and strain or relative humidity and strain significantly influenced the number of parasitised eggs (Table 1). No significant difference was shown between the two strains of *T. cacoeciae* (IT vs TN) at 25 °C (10% RH) and 30 °C (75–100% RH) (Table 4). No eggs were parasitised by the Italian strain of *T. cacoeciae* for all tested relative humidities at 35 °C (Table 4). The number of parasitised eggs differed significantly among the three tested temperatures for each strain (Table 4).

The number of emerged parasitoids significantly differed among *Trichogramma* strains at all relative humidities for each tested temperature ($p < 0.05$) except at 75% RH and 25 °C ($F_{1,29} = 2.313$, $p = 0.139$) (Figure 2). No emerged adults were observed at 35 °C for all tested relative humidities for *T. cacoeciae* Italian strain (Figure 2). There were significant differences between the three tested temperature for the Italian strain ($p < 0.05$) and Tunisian strain ($p < 0.05$) of *T. cacoeciae* (Figure 2). Only the interaction of temperature and relative humidity had no significant effect on the number of emerged parasitoids (Table 3).

G0 vs G1 generation

For the Italian strain, temperature, relative humidity and generation significantly influenced the parasitism rate (Table 5). Only the interaction between temperature or relative humidity and generation had a significant effect on the number of parasitised eggs (Table 5). Parasitism was greater for the G1 than for the G0 generation at 25–30 °C and 10%, 75% and 100% RH. At 35 °C, parasitism decreased markedly for both generations especially for the G1 generation. The one-way ANOVA indicated that there was a significant difference between both generations only at 10 and 75% RH ($p < 0.05$). Concerning the Tunisian strain, only temperature, relative humidity and their interaction significantly impacted the number of parasitised eggs (Table 5). No significant difference was shown between both generations at all tested relative humidities (10%, 75% and 100% RH) ($p > 0.05$). Parasitism decreased for both generations at 35 °C (Table 2, 4).

The emergence rate of both strains was significantly influenced by temperature and relative humidity (Table 6). Only the interaction between temperature or relative humidity and generation had a significant effect on the number of emerged adults for the Italian strain (Table 6). No emergence was recorded for the G1 generation of the Italian strain at 35 °C, while for the Tunisian strain, the number of emerged wasps was lowest for both generations at the same temperature (35 °C). Statistical analysis indicated that there was no significant difference between the two generations at all tested relative humidities regardless of the temperature levels for both strains ($p > 0.05$).

DISCUSSION

Various factors (e.g. climatic conditions, release rate, *Trichogramma* species/strains, host egg quality) may influence the effectiveness of released *Trichogramma* parasitoids against insect pests in the field (Smith 1996; Pizzol et al. 2010; Nagaraja 2013; Cherif et al. 2021). In most cases, failure of these insects to control target pests in biological control programs is linked to lack of adaptation to environmental conditions in the field that may differ from the laboratory rearing systems (Smith 1996; Nagaraja 2013; Cherif et al. 2021). In fact, changes in climate conditions may have an impact on the plant level which may alter the preference

Table 1. Effect of temperature, relative humidity, strain and their interactions on the number of parasitized eggs by the two *T. cacoeciae* strains (It vs TN) in the G0 and G1 generation

	G0 generation			G1 generation		
Variance source	χ^2	df	*p*	χ^2	df	*p*
Temperature	102.31	2	<0.001	883.75	2	<0.001
Relative humidity	19.44	2	<0.001	4.55	2	<0.01
Trichogramma strains	3.46	1	0.06	260.11	1	<0.001
Temperature × Relative humidity	0.82	4	0.51	2.07	4	0.08
Temperature × *Trichogramma* strains	1.12	2	0.29	324.05	2	<0.001
Relative humidity × *Trichogramma* strains	2.49	2	0.22	3.85	2	0.02
Temperature × Relative humidity × *Trichogramma* strains	2.57	4	0.03	1.46	4	0.21

Table 2. Mean number of parasitized host eggs by the two *T. cacoeciae* strains (It vs TN) at different temperatures at 10%, 75% and 100% RH in the G0 generation

T (°C)	*T. cacoeciae* (IT)	*T. cacoeciae* (TN)	Statistical analysis
	10% RH		
25	19.80 ± 7.17 ^{aA}	22.33 ± 6.61 ^{aA}	$F_{1, 29} = 1.13$; $p = 0.29$
30	16.46 ± 6.45 ^{aA}	22.33 ± 5.94 ^{aB}	$F_{1, 29} = 7.17$; $p = 0.01$
35	10.13 ± 7.63 ^{bA}	6.46 ± 3.09 ^{bA}	$F_{1, 29} = 2.27$; $p = 0.14$
Statistical analysis	$F_{2, 44} = 9.03$; $p < 0.001$	$F = 58.06$; $p < 0.0001$	
	75% RH		
25	23.66 ± 6.66 ^{aA}	25.53 ± 6.65 ^{aA}	$F_{1, 29} = 0.58$; $p = 0.45$
30	24.66 ± 5.46 ^{aA}	27.66 ± 6.22 ^{aA}	$F_{1, 29} = 2.33$; $p = 0.13$
35	11.33 ± 5.81 ^{bA}	16.26 ± 5.15 ^{bB}	$F_{1, 29} = 7.85$; $p < 0.001$
Statistical analysis	$F_{2, 44} = 19.39$; $p < 0.0001$	$F = 15.22$; $p < 0.0001$	
	100% RH		
25	17.20 ± 6.55 ^{aA}	16.73 ± 5.48 ^{aA}	$F_{1, 29} = 0.00$; $p = 0.95$
30	18.20 ± 7.70 ^{aA}	19.60 ± 6.14 ^{aA}	$F_{1, 29} = 0.59$; $p = 0.44$
35	8.80 ± 5.44 ^{bA}	6.26 ± 1.98 ^{bA}	$F_{1, 29} = 0.66$; $p = 0.42$
Statistical analysis	$F_{2, 44} = 8.92$; $p < 0.001$	$F = 43.13$; $p < 0.0001$	

Mean ± Standard Error (SE) followed by the same letter do not differ significantly (Duncan test, $p < 0.05$). Capital and lower letters following the means represent comparisons within the line and the column, respectively.

IT = Italian, TN = Tunisian

Table 3. Effect of temperature, relative humidity, strain and their interactions on the adult emergence of two *T. cacoeciae* strains (It vs TN) in the G0 and G1 generation

	G0 generation			G1 generation		
Variance source	χ^2	df	*p*	χ^2	df	*p*
Temperature	485.45	2	<0.001	1091.66	2	<0.001
Relative humidity	61.50	2	<0.001	37.68	2	<0.001
Trichogramma strains	7.98	1	<0.01	4.37	1	0.03
Temperature × Relative humidity	0.704	4	0.59	2.04	4	0.08
Temperature × *Trichogramma* strains	75.75	2	<0.001	254.21	2	<0.001
Relative humidity × *Trichogramma* strains	8.31	2	<0.001	33.81	2	<0.001
Temperature × Relative humidity× *Trichogramma* strains	0.461	4	0.76	3.68	4	<0.001

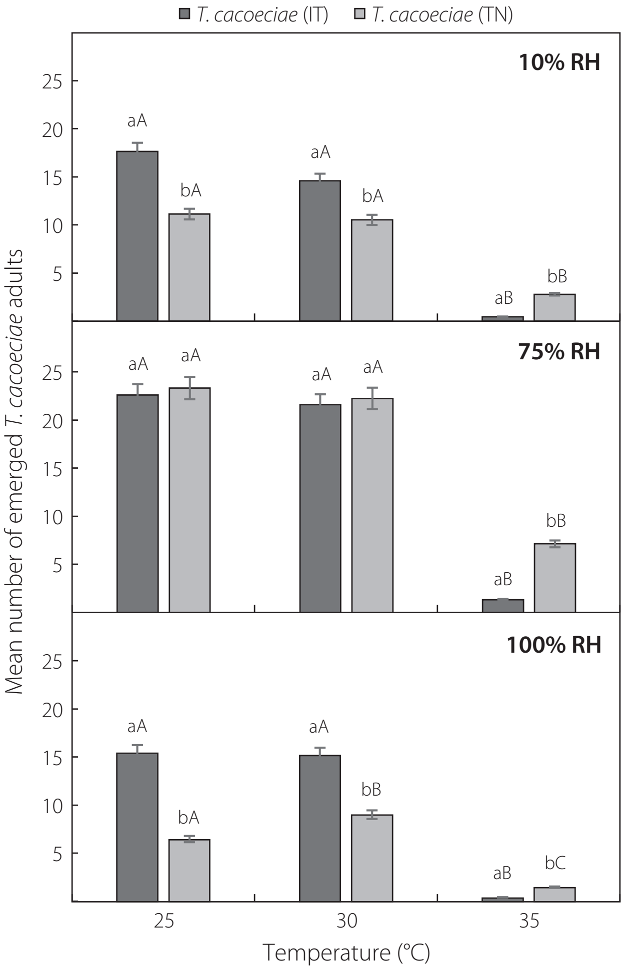

Figure 1. Mean number of emerged adults from parasitised eggs by two *T. cacoeciae* strains at 10, 75 and 100% RH for G0 generation (IT = Italian, TN = Tunisian). Capital and lower-case letters represent comparisons between the relative humidity levels for each *Trichogramma* strain and comparisons between the two *Trichogramma* strains for each relative humidity level respectively. Error bars represent standard errors.

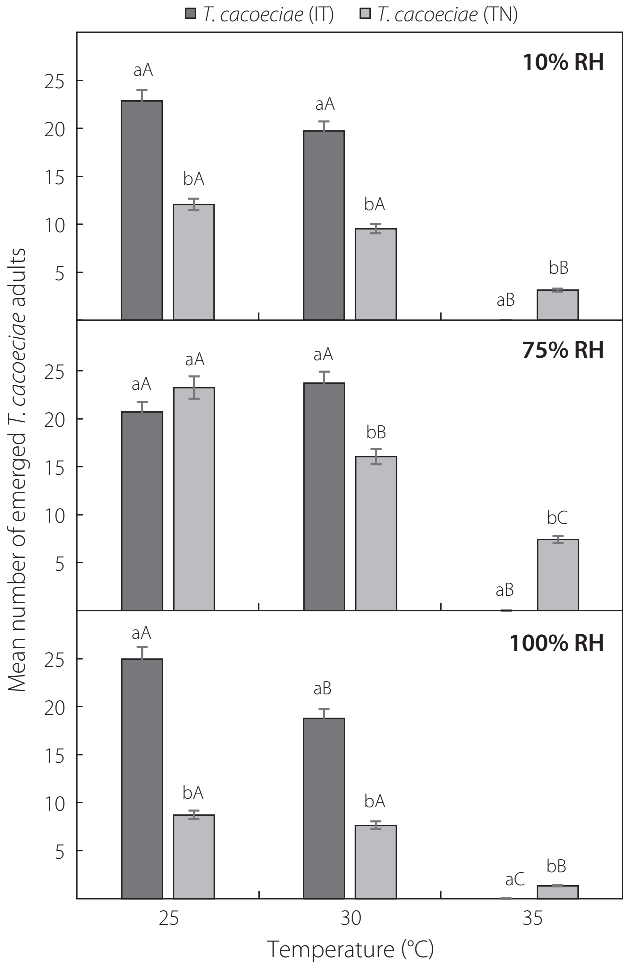

Figure 2. Mean number of emerged adults from parasitised eggs by two *T. cacoeciae* strains at 10, 75 and 100% RH for G1 generation (IT = Italian, TN = Tunisian). Capital and lower-case letters represent comparisons between the relative humidity levels for each *Trichogramma* strain and comparisons between the two *Trichogramma* strains for each relative humidity level respectively. Error bars represent standard errors.

Table 4. Mean number of parasitised *E. kuehniella* host eggs by the two *T. cacoeciae* strains (It ***vs*** TN) at different temperatures at 10, 75 and 100 % RH in the G1 generation

T (°C)	*T. cacoeciae* (IT)	*T. cacoeciae* (TN)	Statistical analysis
	10% RH		
25	23.86 ± 8.71 ^{aA}	23.73 ± 9.11 ^{aA}	$F_{1, 29} = 0.75; p = 0.39$
30	23.00 ± 2.94 ^{aA}	20.00 ± 4.45 ^{bB}	$F_{1, 29} = 5.27; p = 0.02$
35	0 ± 0 ^{bA}	7.73 ± 3.39 ^{cB}	$F_{1, 29} = 422.38; p < 0.0001$
Statistical analysis	$F_{2, 44} = 370.02; p < 0.0001$	$F_{2, 44} = 61.77; p < 0.0001$	
	75% RH		
25	22.93 ± 4.56 ^{aA}	26.93 ± 4.69 ^{aB}	$F_{1, 29} = 5.043; p = 0.03$
30	25.00 ± 5.52 ^{aA}	23.73 ± 7.93 ^{aA}	$F_{1, 29} = 0.64; p = 0.42$
35	0 ± 0 ^{bA}	15.53 ± 4.95 ^{bB}	$F_{1, 29} = 1133.36; p < 0.0001$
Statistical analysis	$F_{2, 44} = 1769.94; p < 0.0001$	$F_{2, 44} = 9.454; p < 0.0001$	
	100% RH		
25	27.26 ± 3.29 ^{aA}	23.20 ± 4.38 ^{aB}	$F_{1, 29} = 7.69; p < 0.01$
30	22.20 ± 15.15 ^{bA}	18.80 ± 6.24 ^{bA}	$F_{1, 29} = 2.82; p = 0.10$
35	0 ± 0 ^{cA}	7.33 ± 3.73 ^{cB}	$F_{1, 29} = 498.48; p < 0.0001$
Statistical analysis	$F_{2, 44} = 2021.65; p < 0.0001$	$F_{2, 44} = 55.698; p < 0.0001$	

Mean ± Standard Error (SE) followed by the same letter do not differ significantly (Duncan test, $p < 0.05$). Capital and lower letters following the means represent comparisons within the line and the column, respectively.

IT = Italian, TN = Tunisian

Table 5. Effect of temperature, relative humidity, generation and their interactions on the number of parasitised eggs for the Italian and Tunisian *Trichogramma* strains

	Italian			Tunisian		
Variance source	χ^2	df	*P*	χ^2	df	*p*
Temperature	1568.11	2	<0.001	241.35	2	<0.001
Relative humidity	6.07	2	0.03	35.40	2	<0.001
Generation	157.23	1	<0.001	0.54	1	0.46
Temperature × Relative humidity	2.56	4	0.63	9.63	4	0.04
Temperature × Generation	600.40	2	<0.001	5.28	2	0.07
Relative humidity × Generation	7.03	2	0.03	2.69	2	0.26
Temperature × Relative humidity× Generation	4.22	4	0.37	3.15	4	0.53

Table 6. Effect of temperature, relative humidity, generation and their interactions on the adult emergence for the Italian and Tunisian *Trichogramma* strains

	Italian			Tunisian		
Variance source	χ^2	df	*P*	χ^2	df	*p*
Temperature	1568.11	2	<0.001	241.35	2	<0.001
Relative humidity	6.07	2	0.03	35.40	2	<0.001
Generation	157.23	1	<0.001	0.54	1	0.46
Temperature × Relative humidity	2.56	4	0.63	9.63	4	0.04
Temperature × Generation	600.40	2	<0.001	5.28	2	0.07
Relative humidity × Generation	7.03	2	0.03	2.69	2	0.26
Temperature × Relative humidity× Generation	4.22	4	0.37	3.15	4	0.53

and performance of insects (Rosenblatt and Schmitz 2016; Han et al. 2019). Temperature and humidity variations could affect some *Trichogramma* characteristics such as parasitism and emergence (Smith 1996; Nagaraja 2013; Cherif et al. 2021).

Our results demonstrate that temperature, relative humidity and strain affected the parasitism rate and emergence of *T. cacoeciae* in the two generations (G0 and G1). Concerning the G0 generation, the Tunisian strain parasitised more eggs than the Italian strain at 30 °C (10% RH) as well at 30–35 °C (75% RH). For the G1 generation, no parasitised eggs were shown by the Italian strain at 35 °C for all tested relative humidities.

Various studies highlight the impact of temperature and relative humidity on biological traits of *Trichogramma* parasitoids. In this context, Pizzol et al. (2010) highlighted the impact of temperature (15, 20, 25 and 30 °C) on the fecundity, emergence and mortality rates of two strains of *T. cacoeciae* (one originating from France and the other from Tunisia) under laboratory conditions. According to these authors, the two strains showed highest fecundity at 25 °C but when reared at 20 or 25 °C for the French strain and at 25 or 30 °C for the Tunisian one. Recently, Tang et al. (2023) determined parasitism of *T. dendrolimi* Matsumura was significantly higher than that of *T. lutea* Girault at high temperatures and relative humidity levels; and, no parasitism was shown by *T. lutea* at 33 °C and 90% RH. According to Yuan et al. (2012), the highest number of parasitised host eggs was obtained by *T. dendrolimi* and *T. japonicum* Ashmead at 18–26 and 30–34 °C, respectively, while the lowest parasitism rate was recorded for *T. ostriniae* (Peng and Chen) at 30–70%RH. In another study, it has been shown that the highest parasitism rate for six Kenyan species collected from different altitudes (*T. sp. nr. mwanzai* from low altitude, *T. sp. nr. mwanzai* from medium altitude, *T. bruni* from high altitude, *T. sp. nr. lutea* from low altitude, *T. sp. nr. lutea* from medium altitude and *T. sp. nr. lutea* from high altitude) was obtained at 25 and 35 °C and relative humidity of 40–50 and 70–80% (Kalyebi et al. 2005b). The fecundity of *T. pretiosum* Riley was lowest at high temperatures (with 18 ova per female below 30 °C compared to 9 above 30 °C) and highest at 80% RH (Calvin et al. 1984).

Our results indicate that the parasitism rate was higher in the G1 compared to the G0 generation at 25–30 °C for all tested RH levels for the Italian strain. While, for the Tunisian strain, no significant difference was shown between the two generations (G0 and G1) regarding the number of parasitised eggs. Recently, Tabebordbar et al. (2022) demonstrated that temperature significantly affected the parasitism of *T. euproctidis* (Girault) female progeny (G1 generation).

In this study, a significant decrease in the number of emerged adults for both strains was registered at high temperature (35 °C) for all relative humidity levels in the G0 generation. However, in the G1 generation, no emerged parasitoids were registered for the Italian strain at 35 °C. For both generations, the emergence rate of the Italian strain was higher than the Tunisian one at 25–30 °C and 10–100% RH.

The impact of both temperature and humidity on the emergence of *Trichogramma* strains/species has already been studied worldwide. In fact, according to Pizzol et al. (2010), the emergence of the French and Tunisian strains of *T. cacoeciae* was high at 15–25 °C and 20–30 °C respectively. It has been shown recently that emergence of *T. dendrolimi* was significantly higher than that of *T. lutea* at 25 °C and 60% RH (Tang et al. 2023). Previously, Gross (1988) reported that the emergence rate of *T. pretiosum* was highest at 32 ± 1 °C and 60–80% RH. This author demonstrated that relative humidity above 80% and below 40% were not suitable for adult emergence of the aforementioned *Trichogramma* parasitoid at all tested temperatures (27, 32, 35, 38 ± 1 °C). According to Lund (1934), desiccation caused by low humidity, can decrease the number of emerged parasitoids. Moreover, the impact of humidity was greater at higher temperatures (Lund 1934). List (1930) demonstrated previously that age and desiccation had a positive impact on the toughness of the chorion of *Sitotroga* host eggs.

Overall, the two strains of *T. cacoeciae* performed best at 25–30 °C and 75% RH when considering the number of parasitised eggs and emerged parasitoids recorded in both generations. However, the Tunisian strain is more adapted to high temperatures (35 °C). Differences in parasitism and emergence for both generations was linked more to temperature variation, especially at 35 °C, compared to relative humidity and strain, despite the clear impact of these factors on parasitism and emergence. In fact, according to Kalyebi et al. (2005a), parasitism rate of six strains of *Trichogramma* parasitoids was affected by temperature and not relative humidity.

Our data showed that RH, strain and especially temperature affected the parasitism and emergence of two strains (Italian and Tunisian) of *T. cacoeciae*. The two tested strains performed well at all tested temperatures (except the highest temperature) and relative humidities and could be considered as promising candidates for biological control programs in the field. According to Tougeron et al. (2020), parasitoids are likely to respond to climate change in similar ways to most other insects, but some responses are unique to parasitoids due to their relationship with the host (e.g. koinobiont versus idiobiont parasitoids) (Tougeron et al. 2020). These variations may affect host-parasitoid relationship and life cycle (Tougeron et al. 2020).

Our results provided useful information on the performance of *Trichogramma* parasitoids at different levels of temperature and RH. However, field trials should be conducted to determine possible differences at variable environmental conditions.

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AUTHOR CONTRIBUTIONS

AC: Conceptualization, methodology, technical and material supports, Resources, performing experiments, formal analysis, investigation, validation, writing the original draft; RAG: Conceptualization, methodology, technical and material supports, Resources, performing experiments, investigation, validation; WH: Technical and material supports, Resources, validation; KG: Conceptualization, methodology, technical and material supports, Resources, supervision, validation.

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CONFLICT OF INTEREST

The authors declare that there is no potential conflict of interest.

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REFERENCES

Alloui-Griza R, Attia S, Cherif A, Hamdi F, Grissa-Lebdi K. 2022. Effectiveness of different management strategies against *Ectomyeloïs ceratoniae* Zeller (Lepidoptera: Pyralidae) in citrus orchards in Tunisia. Oriental Insects 56(4): 561–583. https://doi.org/10.1080/00305316.2022.2030290.

Calvin DD, Knapp MC, Welch SM, Poston FL, Elzinga RJ. 1984. Impact of Environmental Factors on *Trichogramma pretiosum* Reared on Southwestern Corn Borer Eggs. Environmental Entomology 13: 774–780. https://doi.org/10.1093/ee/13.3.774.

Cherif A, Mansour R, Attia-Barhoumi S, Zappalà L, Grissa-Lebdi K. 2019. Effectiveness of different release rates of *Trichogramma cacoeciae* (Hymenoptera: Trichogrammatidae) against *Tuta absoluta* (lepidoptera: Gelechiidae) in protected and open field tomato crops in Tunisia. Biocontrol Science and Technology 29: 149–161. https://doi.org/10.1080/09583157.2018.1542485.

Cherif A, Mansour R, Grissa-Lebdi K. 2021. The egg parasitoids *Trichogramma*: from laboratory mass rearing to biological control of lepidopteran pests. Biocontrol Science and Technology 31(7): 661–693. https://doi.org/10.1080/09583157.2020.1871469.

del Pino M, Gallego JR, Hernández Suárez E, Cabello T. 2020. Effect of Temperature on Life History and Parasitization Behavior of *Trichogramma achaeae* Nagaraja and Nagarkatti (Hym.: Trichogrammatidae). Insects 11(8): 482. https://doi.org/10.3390/insects11080482.

Gross HR. 1988. Effect of temperature, humidity and free water on the number and normalcy of *Trichogramma pretiosum* Riley (Hymenoptera: Trichogrammatidae) emerging from eggs of *Heliothis zea* (Boddie) (Lepidoptera: Noctuidae). Environmental Entomology 17: 470–475.

Hached W, Sahraoui H, Blel A, Lebdi-Grissa K. 2021. Biological control of *Ectomyelois ceratoniae* Zeller (Lepidoptera: pyralidae) using the egg parasitoid *Trichogramma cacoeciae* Marchal (Hymenoptera: trichogrammatidae) in a Tunisian citrus orchard. Journal of Entomology and Zoology Studies 9(3): 98–104.

Han P, Becker C, Sentis A, Rostás M, Desneux N, Lavoir AV. 2019. Global change-driven modulation of bottom–up forces and cascading effects on biocontrol services. Current Opinion in Insect Science 35: 27–33. https://doi.org/10.1016/j.cois.2019.05.005.

Hodgman CD. 1948. Handbook of Chemistry and Physics. 44th edition. Cleveland: Chemical Rubber; p. 3603.

Iqbal A, Hou Y-Y, Chen Y-M, Ali A, Monticelli LS, Desneux N, Zang L-S. 2020. Impact of Trichogramma parasitoid age on the outcome of multiparasitism in the factitious host eggs of Chinese oak silkworm, Antheraea pernyi. Journal of Pest Science 93(4): 1347–1357. https://doi.org/10.1007/s10340-020-01239-1.

Jalali SK, Mohanraj P, Lakshmi BL. 2016. Trichogrammatids. In: Omkar (editor), Ecofriendly Pest Management for Food Security. London: Academic Press. pp. 139–181.

KalyKalyebi A, Overholt WA, Schulthess F, Mueke JM, Hassan SA, Sithanantham S. 2005a. Functional response of six indigenous trichogrammatid egg parasitoids (Hymenoptera: Trichogrammatidae) in Kenya: influence of temperature and relative humidity. Biological Control 32: 164–171. https://doi.org/10.1016/j.biocontrol.2004.09.006.

Kalyebi A, Sithanantham S, Overholt WA, Hassan SA, Mueke JM. 2005b. Parasitism, longevity and progeny production of six indigenous Kenyan trichogrammatid egg parasitoids (Hymenoptera: Trichogrammatidae) at different temperature and relative humidity regimes. Biocontrol Science and Technology 15(3): 255–270. http://dx.doi.org/10.1080/09583150400016886.

List GM. 1930. Some Experiences in Breeding *Trichogramma minlltllm* Riley. Journal of Economic Entomology 23: 342–348. https://doi.org/10.1093/jee/23.2.342a.

Lund HO. 1934. Some temperature and humidity relations of two races of *Trichogramma minutum* Riley (Hym. Chalcididae). Annals of Entomological Society of America 27: 324–340. https://doi.org/10.1093/aesa/27.2.324.

Mills NJ. 2009. Egg parasitoids in biological control and integrated pest management. In: Cônsoli FL, Parra JPR, Zucchi RA (editors), Egg parasitoids in Agroecosystems with Emphasis on *Trichogramma*. New York: Springer. pp. 389–411. https://doi.org/10.1007/978-1-4020-9110-0_15.

Nagaraja H. 2013. Mass production of Trichogrammatid parasitoids. In: Sithanantham S, Ballal CR, Jalali SK, Bakthavatsalam N, editors. Biological control of insect pests using Egg parasitoids. New York: Springer. pp. 175–189. https://doi.org/10.1007/978-81-322-1181-5_8.

Pizzol J, Pintureau B, Khoualdia O, Desneux N. 2010. Temperature-dependent differences in biological traits between two strains of *Trichogramma cacoeciae* (Hymenoptera: Trichogrammatidae). Journal of Pest Science 83(4): 447–452. https://doi.org/10.1007/s10340-010-0327-0.

Querino RB, Zucchi RA, Pinto JD. 2009. Systematics of the Trichogrammatidae (Hymenoptera: Chalcidoidea) with a focus on the genera attacking Lepidoptera. In: Consoli F, Parra J, Zucchi R, (editors), Egg parasitoids in agroecosystems with emphasis on *Trichogramma*. Progress in biological control. New York: Springer. pp. 191–218. https://doi.org/10.1007/978-1-4020-9110-0_7.

Rosenblatt AE, Schmitz OJ. 2016. Climate change, nutrition, and bottom-up and top-down food web processes. Trends in Ecology and Evolotion 31(12): 965–975. https://doi.org/10.1016/j.tree.2016.09.009.

Sokal RR, Rohlf FJ. 1981. Biometry: The principles and practices of statistics in biological research, second ed. New York: Freeman.

Smith SM. 1996. Biological control with Trichogramma: Advances, successes, and potential of their use. Annual Review of Entomology 41: 375–406. https://doi.org/10.1146/annurev.en.41.010196.002111.

Tabebordbar F, Shishehbor P, Ebrahimi E, Polaszek A, Ugine TA. 2022. Effect of Different Constant Temperatures on Life History and Life Table Parameters of *Trichogramma euproctidis* (Hymenoptera: Trichogrammatidae). Journal of Economic Entomology 115(2): 474–481. https://doi.org/10.1093/jee/toac007.

Tang LD, Sun JW, Dai P, Mu MY, Nkunika POY, Desneux N, Zang LS. 2023. Performance of two dominant trichogrammatid species of fall armyworm from China and Africa under contrasted temperature and humidity regimes. Biological Control 179: 105179. https://doi.org/10.1016/j.biocontrol.2023.105179.

Thomson LJ, Macfadyen S, Hoffmann AA. 2010. Predicting the effects of climate change on natural enemies of agricultural pests. Biological Control 52: 296–306. https://doi.org/10.1016/j.biocontrol.2009.01.022.

Tougeron K, Brodeur J, Le Lann C, Van Baaren J. 2020. How climate change affects the seasonal ecology of insect parasitoids. Ecological Entomology 45: 167–181. https://doi.org/10.1111/een.12792.

Vyas-Patel V, Mumford JD. 2018. Morphological variation and strain identification of insects using wings and I^{3}S. BioRxiv. https://doi.org/10.1101/309468. (preprint)

Wajnberg E, Hassan SA. 1994. Biological control with egg parasitoids. Wallingford: CAB International.

Yuan XH, Song LW, Zhang JJ, Zang LS, Zhu L, Ruan CC, Sun GZ. 2012. Performance of four Chinese *Trichogramma* species as biocontrol agents of the rice striped stem borer, *Chilo suppressalis*, under various temperature and humidity regimes. Journal of Pest Science 85: 497–504. https://doi.org/10.1007/s10340-012-0456-8.

Zougari S, Attia S, Zouba A, Lebdi-Grissa K. 2021. Effectiveness of mass trapping and *Trichogramma cacoeciae* (Hymenoptera: Trichogrammatidae) releases against *Ectomyelois ceratoniae* (Lepidoptera: Pyralidae) in Tunisian oases. Biologia (Bratisl) 76(4):1175–1188. https://doi.org/10.2478/s11756-020-00628-2.