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The thermal requirements of the parasitoid wasp *Telenomus busseolae* (Hym.: Platygastridae), reared on *Sesamia nonagrioides* (Lep.: Noctuidae), under laboratory conditions

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Abstract

The egg parasitoid wasp *Telenomus busseolae* Gahan (Hym.: Platygastridae) is the most important natural enemy of *Sesamia* spp. in sugarcane fields of Iran, playing a significant role in regulating host populations. Temperature is the most critical environmental factor affecting the growth and development of parasitoids, and it plays a vital role in their effectiveness. The objective of this study was to investigate the temperature-dependent development of *T. busseolae* on *S. nonagrioides* Lef. (Lep.: Noctuidae). Thermal requirements of *T. busseolae* were assessed at seven constant temperatures (15, 18, 20, 25, 30, 35, and 37 ºC), and developmental rates were modeled as a function of temperature using two linear and eight nonlinear models. The results showed a significant effect of temperature on the pre-adult developmental duration of male and female parasitoids. From 18 to 35°C, the total preimaginal period decreased from 45.12 to 11.8 days for males and from 46.07 to 12.12 days in females. The developmental time between male and female parasitoids was significantly different at all tested temperatures. The lower temperature threshold (T_0) was determined to be 12.49°C for males and 12.47°C for females, with thermal constant (K) of 250.54 and 259.69 DD, respectively, using Ikemoto and Takai linear model. The Logan 6 model fitted the data well in both male and female parasitoids, and therefore it was recommended for describing the temperature-dependent development of this parasitoid. These findings can be useful for the mass rearing and application of *T. busseolae* in the biological control of sugarcane stem borers.

Keywords: linear and nonlinear models, thermal constant, degree-day, biological control

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نیازهای دمایی زنبور پارازیتویید *Telenomus busseolae* (Hym.: Platygastridae) پرورش یافته روی *Sesamia nonagrioides* (Lep.: Noctuidae) در شرایط آزمایشگاهی

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چکیده

زنبور پارازیتویید تخم *Telenomus busseolae* Gahan مهمترین دشمن طبیعی ساقه‌خواران *Sesamia* spp. در مزارع نیشکر ایران است که نقش قابل توجهی را در تنظیم جمعیت آفت دارد. دما مهم‌ترین عامل محیطی است که رشد و نمو پارازیتویید هارا تحت تأثیر قرار می‌دهد و روی کارآیی آنها نیز موثر است. هدف از این مطالعه شناخت ارتباط بین دما و رشد و نمو پارازیتویید *T. busseolae*، روی *Sesamia nonagrioides*، است. نیازهای دمایی زنبور *T. busseolae* روی *S. nonagrioides* در هفت دمای ثابت ۱۵، ۱۸، ۲۰، ۲۵، ۳۰، ۳۵ و ۳۷ درجه سلسیوس مورد بررسی قرار گرفت. ارتباط رشد و نمو مراحل نابالغ زنبوربا دما با دو مدل خطی و هشت مدل غیرخطی نیز مورد بررسی قرار گرفت.. نتایج نشان داد که دما تأثیر معنی‌داری روی دوره رشدی قبل از بلوغ در هر دو جنس نر و ماده پارازیتویید دارد. طول دوره قبل از بلوغ با افزایش دما از ۱۸ به ۳۵ درجه سلسیوس، به‌ترتیب از ٤٥/١٢ به ١١/٨ روز در پارازیتویید نر و در پارازیتویید ماده از ٤٦/٠٧ به ١٢/١٢ روز کاهش یافت. طول دوره روشد و نمو بین پارازیتویید نر و ماده در همه دماهای مورد بررسی اختلاف معنی‌داری نشان داد. با استفاده از مدل خطی Ikemoto & Takai آستانه پایین دمایی برای زنبور نر و ماده به ترتیب ١٢/٤٩ و ١٢/٤٧ درجه سلسیوس و نیاز گرمایی نیز به ترتیب ٢٥٠/٥٤ و ٢٥٩/٦٩ روز- درجه تعیین شد. در میان مدل‌های غیرخطی، مدل Logan 6 با توجه به اینکه رابطه نرخ رشد و نمو و دما را در هر دو جنس نر و ماده پارازیتویید به‌بهترین نحو توصیف نموده، به عنوان مناسب‌ترین مدل معرفی می‌شود. یافته های حاصل از این تحقیق در پرورش انبوه *T. busseolae* و کاربرد آن در مهار زیستی ساقه‌خواران نیشکر می‌تواند مورد استفاده قرار گیرد.

کلید واژه‌ها: مدل‌های خطی و غیرخطی، ثابت گرمایی، روز-درجه، مهار زیستی

دبیر تخصصی: دکتر آرش راسخ

Introduction

The stem borers, *Sesamia cretica* Led. and *S. nonagrioides* Lef. (Lep.: Noctuidae) are major pests of sugarcane fields in Khuzestan province, causing both quantitative and qualitative damage to sugarcane crops if not managed. Additionally, the feeding activity of stem borer larvae provides favorable conditions for the activity of fungi and other saprophytic microorganisms, thereby intensifying the damage (Daniali, 1985; Askarianzadeh et al., 2008). *Sesamia* spp. stem borers cause damage to the stems and internodes of sugarcane in both plant and ratoon fields (Jamshidnia, 2023a). The damage caused by the pests leads to the death of the central bud during the tillering stage, injury to internodes during stem formation, and reduction in both sugar quantity and quality at crop maturity (Cheraghi et al., 2018; Ebrahimifar et al., 2023).

The egg parasitoid, *Telenomus busseolae* Gahan, is one of the most well-known parasitoids of cereal stem borers of the genera *Busseola* and *Sesamia*, and has been reported from various regions of the world (Polaszek,1998). *T. busseolae* is the most important natural enemy of *Sesamia* spp. in Khuzestan sugarcane fields and plays a significant role in regulating host populations (Jamshidnia et al., 2010). Parasitism rates of *Sesamia* spp. eggs in corn and sugarcane fields in Khuzestan have been reported to reach 90% (Abbasipour, 2004). This parasitoid parasitizes up to 84.4% of stem borer eggs in plant cane fields and up to 87.3% in ratoon fields (Jamshidnia, 2023b). Various factors, including host species, plant varieties, temperature, and humidity, may influence the efficacy of the parasitoid wasp *T. busseolae*. Among these, temperature has the most significant impact as it is the most critical environmental factor affecting the growth and development of poikilothermic organisms, including insects (Wigglesworth, 1972).

In addition to its directly affecting on the growth and development of parasitoids, temperature plays a vital role in their physiology and overall effectiveness (Hance et al., 2007; Colinet et al., 2015). Numerous studies have examined the effect of temperature on the biology and performance of *T. busseolae*, including investigations on its development on the eggs of corn stem borer *S. calamistis* and *Busseola fusca* at various temperatures (Chabi-Olaye et al., 1997; Okoth et al., 2006). Similarly, several studies have evaluated the effects of temperature on the biology, population growth, and functional response of *T. busseolae* on *S. cretica* and *S. nonagrioides* (Jamshidnia et al., 2010; Jamshidnia & Sadeghi, 2014a, b; Cheraghi et al., 2018b). Temperature-dependent growth and development models are effective tools for assessing the impact of temperature on the growth and survival of poikilothermic organisms, including insects. These models describe the relationship between temperature and development rate: linear models are commonly used to estimate the lower temperature threshold, while nonlinear models provide a more accurate description over a wider temperature range, allowing estimation of upper thresholds and temperature (Malekera et al., 2022; Régnier et al., 2022). These models can also be used to predict the timing of pests and natural enemy emergence in the field (Zamani et al., 2007). Determining thermal requirements and temperature thresholds provides valuable information for the mass rearing and field application of biological control agents (Rodrigues et al., 2013).

Understanding the adaptations of biological control agents to environmental conditions is crucial. The use of *T. busseolae* as a biological control agent of sugarcane stem borers has been successful; however, knowledge of its thermal requirements is essential for improving mass rearing. The

objective of this study was to determine the relationship between temperature and developmental rates, as well as the lower temperature threshold and thermal requirements of *T. busseolae,* both linear and nonlinear models were evaluated. Since temperature may affect males and females differently, the two sexes were studied separately. The results provide valuable information for the optimal use of this biological control agent in sugarcane stem borer management programs.

Materials and Methods

Rearing of the Parasitoid

The initial colony of the parasitoid wasp, *T. busseolae* was established from parasitized egg masses of sugarcane stem borers collected from sugarcane fields at the Amir Kabir Agro-Industry (located at 48°12' - 48°30' East longitude and 31°15' to 31°40' N latitude in Khuzestan province, Iran). To rear the parasitoid, eggs of *S. nonagrioides* were maintained under laboratory conditions following the method described by Ranjbar Aghdam (1999). The *T. busseolae* colony was maintained in an incubator at 27 ± 1°C, 65 ± 5% relative humidity, and a photoperiod of 16:8 h (l:D).

Effect of temperature on parasitoid development

The pre-adult developmental duration of *T. busseolae* on *S. nonagrioides* was evaluated at temperatures of 15, 18, 20, 25, 30, 35, and 37°C, with a relative humidity of 65 ± 5% and a photoperiod of 16:8 h (l:D). For each experiment, five one-day-old mated female wasps were selected and individually placed in test tubes (17 cm long, 2.5 cm diameter). Each female was provided with 50 freshly laid host eggs and maintained in an incubator at 27 ± 1°C and 65 ± 5% relative humidity for six hours. Previous studies indicate that *T. busseolae* can complete more than half of its oviposition within the first six hours after emergence if sufficient host eggs are available (Chabi-Olaye et al., 1997).

Subsequently, the female wasp was removed, and the parasitized eggs were incubated at the specified temperatures. Egg masses were inspected twice daily (early morning and late afternoon) until adult emergence, and the sexes of emerging parasitoids were determined based on their antennae.

Developmental rate models

The developmental rate (reciprocal of developmental duration) was calculated using data on developmental duration at different temperatures. The resulting data were then fitted to two linear models and several commonly used nonlinear models in this field.

The ordinary linear (degree-day) model, one of the most common models to determine the thermal constant and lower developmental threshold (zero development), was applied (Campbell et al., 1974). The degree-day model is as follows:

$$\frac{1}{D} = -\frac{t}{K} + \frac{1}{K}T$$

Another linear model used in this study was the Ikemoto and Takai model (Ikemoto and Takai, 2000):

$$DT = K + tD$$

Where, D: Developmental duration in days, K: Thermal constant, T: Lower developmental threshold (T_0), t: Rearing temperature.

Eight nonlinear models were used to describe the temperature-dependent development of the *T. busseolae* as summarized in Table 1.

Model selection criteria and data analysis

Key criteria for evaluating model accuracy included the coefficient of determination (R^2), the adjusted coefficient of determination (R^2_{adj}), and the residual sum of squares (RSS). These indices indicate the goodness of fit and the predictive performance of the models. Higher R^2 and R^2_{adj} values, along with lower RSS values, correspond to a better fit. However, for comparing models with different numbers of parameters, (R^2) and RSS alone are insufficient. Therefore, the Akaike Information Criterion (AIC) was also applied, calculated as follows (Akaike, 1974; Vucetich et al., 2002):

$$AIC = n\ln\left(\frac{RSS}{n}\right) + 2p$$

Where,
p: The number of parameters,
n: The number of observations
Lower AIC values indicate higher model accuracy. In addition to statistical criteria, the value of the bioclimatic parameters such as T_{max}, T_{min} and T_{opt} can be used in model selection.
One-way analysis of variance (ANOVA) was performed to compare the effect of different temperatures on the pre-adult development of *T. busseolae*. Post-hoc mean comparisons were performed using Tukey's test. A student's t-test was employed to compare developmental time between male and female parasitoids. The temperature-dependent models were analyzed using the Levenberg-Marquart algorithm in JMP (SAS Institute, 2003)

Results

Developmental duration of immature *T. busseolae* at different temperatures

No emergence occurred at 15°C despite successful parasitization of host eggs, and at 37°C, the host eggs shrivelled and became unsuitable for embryonic development of the wasp. Therefore, comparisons were made at the remaining five temperatures.
Analysis of variance results revealed a significant effect of temperature on the pre-adult developmental duration of male (F = 12656.5; df = 4, 178; $P < 0.0001$) and female (F = 12957.6; df = 4, 342; $P < 0.0001$) wasps. As the temperature increased, the developmental duration of immature wasps decreased. From 18 to 35°C, the pre-adult developmental duration decreased from 45.12 to 11.8 days for males and from 46.07 to 12.12 days for females (Table 2). The developmental time of female parasitoid was significantly longer than that of males at all tested temperatures (Table 2).

Table 1. Nonlinear models used to describe the temperature-dependent development of the *Telenomus busseolae*

Model	Equation	Reference
Logan 6	$\frac{1}{D} = \psi\left[e^{\rho T} - e^{(\rho T_{max} - (\frac{T_{max}-T}{\Delta T}))}\right]$	Logan *et al.* (1976)
Lactin 1	$\frac{1}{D} = e^{\rho T} - e^{\rho T_L - (\frac{T_L - T}{\Delta T})}$	Lactin *et al.* (1995)
Harcourt	$\frac{1}{D} = aT^3 + bT^2 + cT + d$	Harcourt & Yee (1982)
Briere 1	$\frac{1}{D} = aT(T - T_0)(T_{max} - T)^{1/2}$	Briere et al. (1999)
Janish-Rochat	$\frac{1}{D} = \frac{2C}{a^{T-T_m} + b^{T_m - T}}$	Rochat & Gutierrez (2001)
Stinner	$\frac{1}{D} = \begin{cases} \frac{Max - Dev - rate \times e^{a+bT_{opt}}}{1+e^{a+bT}} if T \le T_{opt} \\ \frac{Max - Dev - rate \times e^{a+bT_{opt}}}{1+e^{a+b(2T_{opt}-T)}} if T \rangle T_{opt} \end{cases}$	Stinner *et al.*, (1974)
Davidson	$\frac{1}{D_i} = \frac{k}{1+e^{a-bT_i}}$	Davidson (1944)
Kontodimas	$\frac{1}{D} = a(T - T_{min})^2(T_{max} - T)$	Kontodimas *et al.*, (2004)

Lower Developmental Threshold and Thermal Requirements

Regression analysis between temperature and developmental rate using the ordinary linear model showed a significant linear relationship for males (F = 89.52; df = 1, 3; P = 0.0025) and females (F = 93.90; df = 1, 3; P = 0.0023). The fitted regression line, shown in Figure 7, confirmed a linear relationship with a high coefficient of determination.

Using the Ikemoto and Takai model, a significant linear relationship was also observed for males (F = 309.93; df = 1, 3; P = 0.004) and females (F = 293.38; df = 1, 3; P = 0.004). The Ikemoto and Takai model generally exhibits higher R^2 and significance levels compared to the ordinary linear model.

The T_0 and thermal requirements were determined separately for male and female immature stages using both linear models. In the ordinary linear model, the lower temperature threshold was 12.26°C for males and 12.35°C for females, thermal constants (K) of 254.45 and 261.10 degree-days, respectively. In the Ikemoto and Takai model, the lower temperature threshold was 12.49°C for males and 12.47°C for females, thermal constants of 250.54 and 259.69 degree-days (DD), respectively.

Table 2. Mean of developmental time (±SE) of the immature stages of parasitoid wasp, *Telenomus busseolae* at different temperatures.

Temperature(°C)	Developmental time (days)						
	n	Male	n	Female	df	T	P
18	50	45.12±0.168Ba	43	46.07±0.189Aa	91	-3.77	0.0003
20	65	32.99±0.099Bb	67	34.56±0.142Ab	120	-7.83	< 0.0001
25	36	21.48±0.214Bc	47	22.36±0.142Ac	81	-2.84	0.0057
30	72	12.81±0.060Bd	87	13.26±0.052Ad	157	-5.3	< 0.0001
35	36	11.80±0.107Be	49	12.12±0.086Ae	84	-2.94	0.0232

Means followed by different small letter in column and different capital letter in row are statustically different at P < 0.05

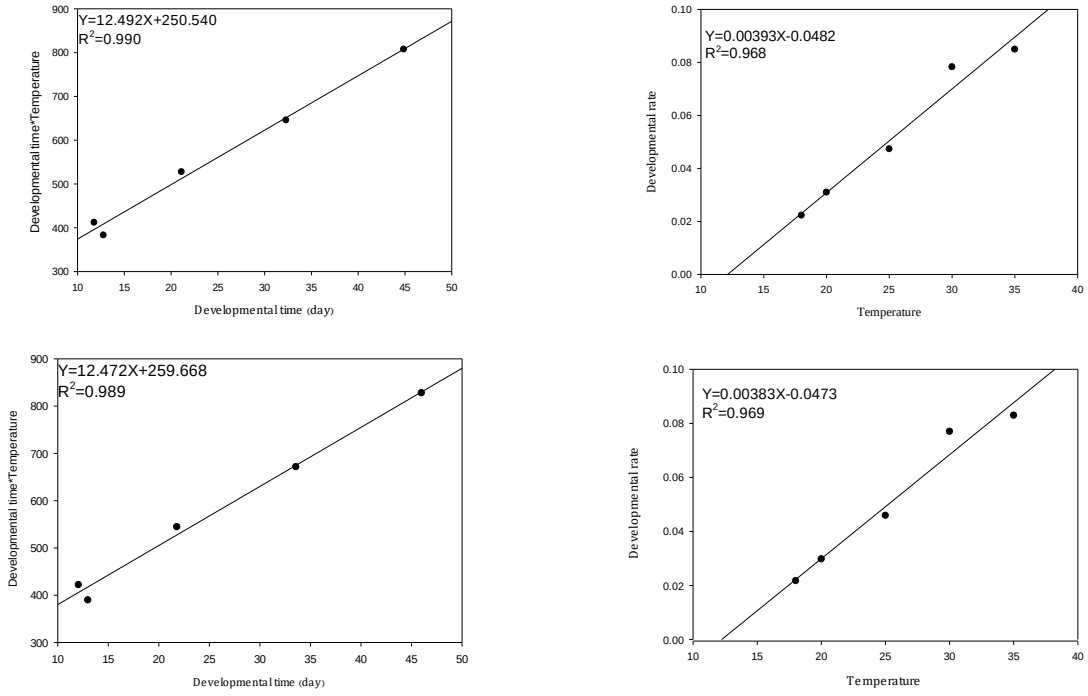


Figure 1. Fitting the linear models (left: Ikemoto and Takai model; right: ordinary linear model) to observed values of developmental rate of *Telenomus busseolae* immature stages

Nonlinear models

Results of parameter estimation and data description using nonlinear models for male and female wasps are presented in Table 3 and Figures 2 and 3.

The goodness of fit for the nonlinear models is presented in Tables 4 and 5 for male and female wasps, respectively. Models were ranked based on R^2, R^2_{adj}, RSS, and AIC. The higher value of R^2 (0.99), R^2_{adj} (0.99), and lower estimate of AIC (Male: -61.3, Female: -63.2) showed that the Logan 6 and Janish-Rochat models, provided the best descriptions of immature stage development for both male and female parasitoid. The Stinner model successfully described this relationship in males (R^2=0.99, R^2_{adj}=0.99, AIC=-61.32) and was ranked as a suitable model; however, it failed to do so in females (R^2=0.56, R^2_{adj}=0.49, AIC=-32.23). Thus, the descriptive power of models differs between sexes.

Discussion

This study found that the developmental duration of the immature stages of the *T.busseolae* decreased as temperatures increased from 18 to 35°C. A similar trend was reported for the developmental duration of this parasitoid on *S. cretica* eggs (Jamshidnia, 2021).

Table 3. Estimated parameters of the nonlinear models fitting to immature developmental rate of *Telenomus busseolae*

Model	Parameter	Male	SE	Female	SE
Logan6	ψ	0.00386	0.000111	0.00369	0.000916
	p	0.10024	0.0126	0.1006	0.0108
	T_{max}	35.7	3.534	35.65	8.557
	ΔT	0.667	2.880	0.5648	6.997
Lactin 1	P	-0.01006	0.0194	-0.00807	0.02027
	T_{max}	13.99	2.647	13.812	2.853
	ΔT	-61.026	9.127	-72.82	13.237
Harcourt	A	-0.000029	0.0000194	-0.000029	0.000018
	B	0.00228	0.00155	0.00229	0.00145
	C	0.0535	0.0402	0.0542	0.0376
	D	0.4176	0.3380	0.4259	0.3161
Briere 1	A	0.0000378	0.0000120	0.000035	0.000012
	T_{min}	11.88	2.490	11.76	2.668
	T_{max}	42.89	4.031	43.44	4.644
Janish-Rochat	C	0.0674	0.1306	0.0650	0.2076
	A	0.905	0.0114	0.9043	0.0098
	T_m	35.45	1.777	35.42	3.044
	B	0.256	1.510	0.2163	2.615
Stinner	T_{opt}	32.93	0.2489	35.28	4.176
	K_1	1.307	1.198	0.3194	0.1968
	K_2	5.882	0.860	5.343	0.6122
	c	-0.104	0.0384	-0.1373	5.231
Davidson	c	0.0977	0.0138	0.0961	0.0143
	a	4.822	0.989	4.863	0.9702
	b	-0.197	0.0530	-0.193	0.0523
Kontodimas	a	.000008	0.0000051	0.0000073	0.000050
	T_{min}	9.17	2.254	9.02	2.689
	T_{max}	51.14	7.922	52.11	9.062

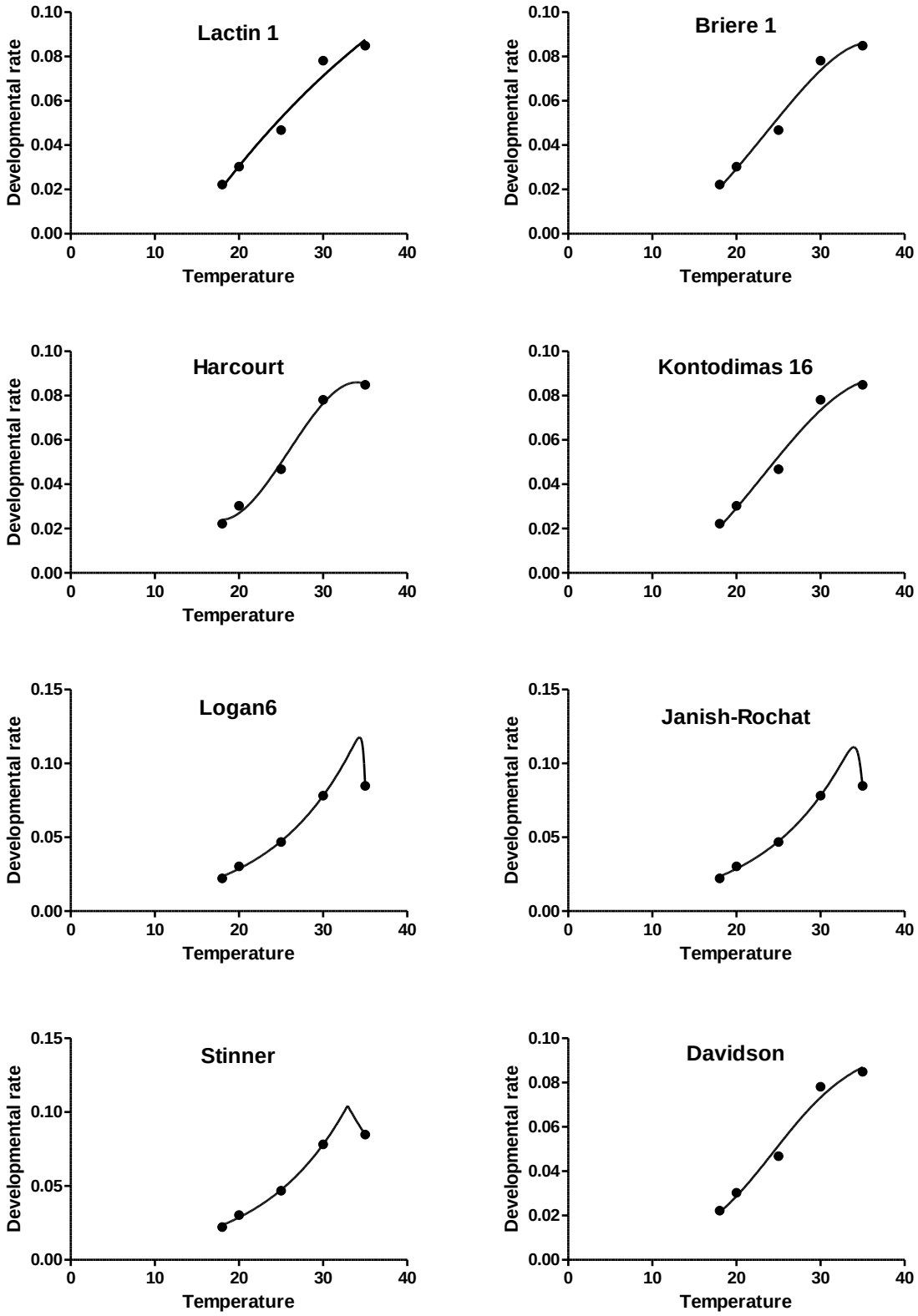


Figure 2. Fitting the nonlinear models to observed values of developmental rate of immature stages of male wasp, *Telenomus busseolae*

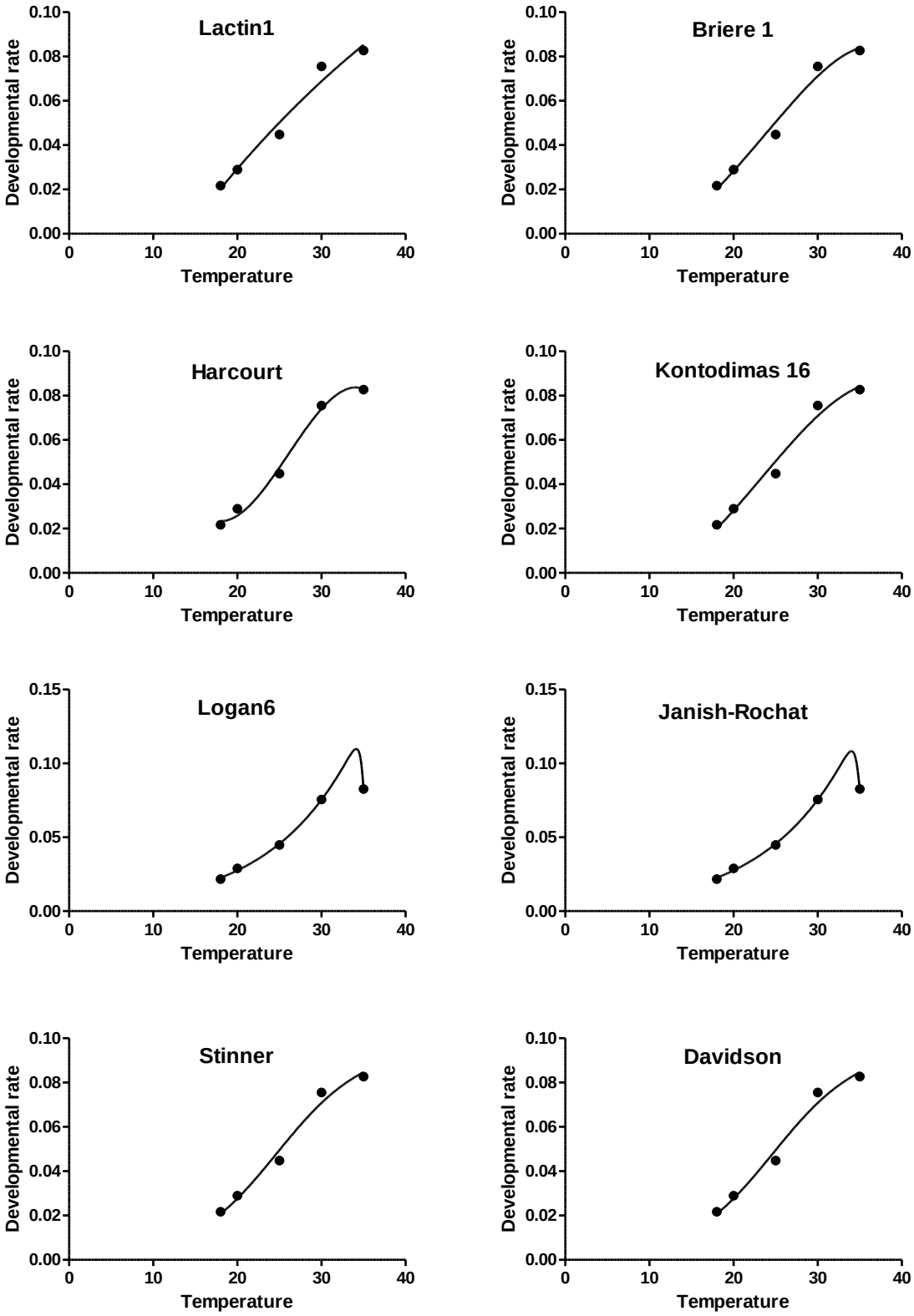


Figure 3. Fitting the nonlinear models to observed values of developmental rate of immature stages of female wasp, *Telenomus busseolae*

Table 4. Comparison of nonlinear models for description of immature developmental rate of male parasitoid, *Telenomus busseolae*

Model	Statistical criteria			
	R^2	R^2_{adj}	RSS (10^{-5})	AIC
Logan 6	0.999	0.994	8.710	-61.391
Lactin 1	0.972	0.889	0.615	-48.789
Harcourt	0.992	0.967	2.585	-52.863
Briere 1	0.983	0.930	5.508	-51.081
Janish-Rochat	0.999	0.994	0.470	-61.390
Stinner	0.998	0.994	0.476	-61.325
Davidson	0.983	0.932	5.389	-51.192
Kontodimas	0.981	0.925	5.939	-50.704

Table 5. Comparison of nonlinear models for description of immature developmental rate of female parasitoid, *T. busseolae*

Model	Statistical criteria			
	R^2	R^2_{adj}	RSS(10^{-5})	AIC
Logan 6	0.999	0.996	0.324	-63.247
Lactin 1	0.972	0.889	8.304	-49.028
Harcourt	0.992	0.970	2.261	-53.533
Briere 1	0.982	0.927	5.462	-51.123
Janish-Rochat	0.999	0.996	0.324	-63.244
Stinner	0.561	0.487	131.102	-32.232
Davidson	0.983	0.932	5.082	-51.484
Kontodimas	0.980	0.922	5.825	-50.801

Research on *T. busseolae* and *T. isis* from maize fields in Benin, Africa, indicated that these wasps failed to complete development or emerge from egg masses of the maize stem borer *S. calamistis* at 15 and 34°C. For *T. busseolae*, the developmental duration decreased from 42.7 to 12.2 days across temperatures from 18 to 30°C (Chabi-Olaye et al., 1997, 2001), which is consistent with the developmental durations observed in this study. However, the population examined here exhibited greater tolerance to higher temperatures, completing development and emerging from hosts at 35°C. Similarly, a study on *Trichogramma podisi* Ashmead demonstrated that increasing temperatures from 15 to 30°C reduced the immature developmental duration on *Dichelops melacanthus* (Dallas) eggs to 48 days and on *Podisus nigrispinus* (Dallas) eggs to 56.3 days (Taguti et al., 2019). Comparable results were reported for *T. remus* (Nixon) on various *Spodoptera* species (Pomari et al., 2013). The inverse relationship between temperature and developmental duration, observed here and in other studies, results from increased metabolic activity in parasitoids. Enhanced metabolism accelerates developmental rates, which can benefit biological control by enabling quicker adult emergence; However, elevated temperatures may reduce parasitism rates (Bueno et al., 2009). In the present study the developmental time of *T. busseolae* was significantly different by gender, with males developing faster than females. Earlier male emergence has also been reported in other parasitoids of Platygastridae and Trichigrammatidae (Bayram et al., 2004). This strategy promotes male reproductive success by ensuring the availability of females for mating (Fantinou et al., 1998). Under field conditions, *T. busseolae* attacks concealed host egg masses beneath leaf

sheaths, allowing first-emerging males to mate before dispersal.

To estimate the T_0 and thermal requirements, two linear models—the ordinary linear model and the Ikemoto and Takai model—were applied. The two models showed minimal differences in estimating the lower developmental threshold and thermal requirements for the immature stages of *T. busseolae*. However, due to the higher coefficient of determination R^2 and greater statistical significance of its parameters, the Ikemoto and Takai model is recommended for determining these values. On *S. cretica*, the lower developmental thresholds for male and female *T. busseolae* were 12.44°C and 12.5°C, respectively, with thermal requirements of 250 and 255 degree-days for males and females, respectively (Jamshidnia, 2021), aligning with the findings of this study. Chabi-Olaye et al. (1997) estimated the lower developmental threshold and thermal requirements for the African population of *T. busseolae* on *S. calamistis* eggs using a linear model as 13.7°C and 204 degree-days, respectively, with no emergence at 34°C. In this study, the lower developmental threshold was approximately 1.2°C lower, and thermal requirements were about 50 degree-days higher, with development continuing at 35°C. For *T. remus* on *Spodoptera frugiperda* (Smith) and *S. litura* eggs, the lower developmental threshold and thermal requirements were estimated at 13°C and 140 degree-days, respectively (Chen et al., 2021). Variations in thermal requirements are common among different species and populations of the same species from distinct geographical origins (Honek, 1996). The *T. busseolae* population in this study appears to tolerate a broader temperature range than the African population, suggesting that temperature responses vary among populations. The lower temperature threshold of S. *cretica* is 12.34 °C as reported by Cheraghi *et al.* (2018) and equal to the estimated T_0 for parasitoids in our study. When there is a synchrony between host and parasitoid, the level of parasitism is high (Hance *et al.,* 2007). A potentially significant effect on the parasitoid's development within its host is favored by the synchronization of the parasitoid's T_0 and its host (Nanga *et al.,* 2021). The ability of models to characterize the relationship between developmental rate and temperature varied, with some providing better fits. Not all parameters in nonlinear models have biological significance; for instance, the Harcourt and Davidson logistic models include parameters lacking biological meaning.

Among the evaluated models, the Logan 6 model ranked highly for both males and females, effectively describing the relationship between developmental rate and temperature.

The estimated lower developmental threshold for *T. busseolae*, irrespective of sex, was approximately 12.5°C. The Kontodimas 16 estimated a threshold of 9°C, the Briere 1, 12°C, and the Lactin 1, 14°C. Analysis of the Kontodimas 16 showed that its lower developmental threshold was not statistically significant, and the Lactin 1 model exhibited poor descriptive power based on model rankings. In contrast, the Briere 1 model effectively described the data, with its estimated lower developmental threshold closely matching that of the linear model.

The T_{max} were estimated at 35.7°C and 35.5°C by the Logan 6 and Janiš-Rochat models, respectively, and at 43°C and 51–52°C by the Briere 1 and Kontodimas 16 models, respectively. This parameter was statistically significant in the Briere 1 and Kontodimas 16 models but not in the others. The T_{opt} for males was estimated at 33°C by the Stinner model.

Different nonlinear models vary in their ability to accurately estimate biologically meaningful parameters. Estimated threshold temperatures may lack precision due to inherent limitations in fitting developmental rate data across a wide

temperature range. Although a single model is often preferred in practice, relying exclusively on one model to predict developmental rates and estimate biological parameters may not always be reliable (Roy et al., 2002). Nonlinear models are usually used to evaluate insect response to extreme temperatures (Baptiste et al., 2021). In contrast, linear models can be effective under field conditions, as insects typically experience temperatures within a near-linear range. While insects can survive a broad temperature spectrum, their growth rate usually exhibits a linear pattern within the typical environmental temperature fluctuations (Dadlani et al., 2025). This linear relationship makes the linear model a practical and useful tool for predicting insect development.

The lower developmental threshold and thermal constant are critical for predicting insect development in field conditions. By determining the lower developmental threshold, the accumulated thermal units acquired by the insect in the field can be calculated and compared to the thermal constant to assess developmental progress. When temperature fluctuations are substantial, the relationship between temperature and developmental rate becomes nonlinear, potentially limiting the applicability of linear models. However, research suggests that linear models remain effective in many cases, as insects in the field typically experience temperature ranges where the relationship is linear. Extreme temperatures, where nonlinear relationships dominate, are rarely encountered. Thus, linear models can be practical for field applications (Campbell et al., 1974).

Knowledge of parasitoid thermal requirements is essential for mass-rearing programs (Chia et al., 2018) and for determining optimal storage temperatures (Chen et al., 2021). Bayram et al. (2005) recommended 12°C as the ideal temperature for long-term storage of *T. busseolae*, which matches the lower developmental threshold identified in this study. These results have useful applications for the biological control of sugarcane stem borers and mass rearing of *T. busseolae*. The findings provide valuable insights for optimizing the mass production of this parasitoid and enhancing the efficacy of this biological control agent in sugarcane fields. The results of this research can be used in predictions of occurrence, number of generations, and releasing time of *T. busseolae*. While laboratory studies assessing parasitoid performance at constant temperatures provide valuable data, they don't fully capture the complexities of field conditions where temperatures fluctuate diurnally. This difference can significantly impact the parasitoid's development, survival, and ultimately, its effectiveness in biological control.

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