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Temperature-Dependent Development and Temperature Thresholds of total immature stage of Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann, 1824) (Diptera: Tephritidae) in Iran

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Abstract

Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann, 1824) (Diptera: Tephritidae), is one of the most important pests of agricultural crops in tropical and subtropical regions of the world. In this study, the developmental rate of *C. ceratitis* was studied at 10, 12, 15, 17, 20, 25, 27, 30, 32, and 35°C. The results showed a nonlinear relationship between temperatures and developmental rate. The best nonlinear models were Perfomance-1 and Performance-2 in the Mazandaran and Fars provinces, respectively. These models simulated the developmental rate of Mediterranean fruit fly accurately at temperatures ranging from 15 to 35 and 20 to 30°C, in the Mazandaran and Fars provinces, respectively and the estimated optimal temperature of total immature stages was 31.94 and 31.8°C, respectively. The lower and upper temperature thresholds the total immature stage in Mazandaran and Fars provinces were estimated at 11.23 and 13.15 °C, and 38.1 and 37.74 °C, respectively. Between two linear models, the Ikemoto linear model, showed better-fit data compared with the ordinary model.

Keywords: *Ceratitis capitata*, Nonlinear models, Linear models, Developmental rate, Fars, Mazandaran.

Introduction:

Fruit flies belong to the family Tephritidae, one of the largest and most economically important groups in the order Diptera (White and Elson-Harris, 1992; Li *et al*., 2013). The larvae of most Tephritid species develop in the seed and cause severe damage to fruit and vegetable crops in most tropical and subtropical countries. The Mediterranean fruit fly is one of the most damaging agricultural pest in the world. It is a severe pest of more than 350 species of fruits and vegetables (Thomas *et al*., 2001; Morales *et al*., 2007; White and Elson-Harris, 1992). In the last decade, the consequences of climate change on the distribution, abundance, and phenology of insect species

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have been widely studied. With an estimated further increase in mean global temperatures of 0.8°C over the next 100 years, the biosphere can be expected to experience broad climate-related changes. The occurrence of insect pests could be impacted by these changes. Insects may respond to climate change in a variety of ways (Chandrakumara *et al*., 2023; Kambrekar *et al*., 2015; Yamamura and Kiritani, 1998). Various factors, particular among them, temperature, is a critical abiotic factor affecting the development, survival, and reproduction of insect species, fitness, or performance-related traits of insects (Azrag *et al*., 2018; Yadav *et al*., 2014). Insect distribution and abundance are highly affected by temperature and generally, an increase in temperature within the limits tolerated by the insect results in a rapid population increase (Campbell *et al*., 1974; Bale *et al*., 2002; Mujica *et al*., 2017).

The developmental rate of insects and other poikilothermic invertebrates is linearly dependent on temperature from a lower developmental threshold (T_{min}) to the optimum temperature (T_{opt}). This is because temperature affects many physiological processes and the activity of enzymes (Trudgill *et al*., 2005). Phenological models, using physiological time data, have been developed for Mediterranean fruit fly to predict the emergence of adults from the overwintering generation, egg hatching, larval, and pupal development, as well as generation time. These models, all based on a linear relationship between temperature and developmental rate, have been used to time pesticide application for Mediterranean fruit fly (Duyck *et al*., 2002; Grout and Stoltz, 2007; Duyck and Quilici, 2002). Linear approximation enables the estimation of lower temperature thresholds and thermal constants within a limited temperature range (Campbell *et al*., 1974; Hone ˇk 1999; Howell and Neven, 2000; Jaros ˇik *et al*., 2002).The curvilinear models have not been routinely used of their complexity (Howell and Neven, 2000). Temperature is the single most important environmental factor determining development and survival of Tephritid fruit flies (Fletcher, 1989). Temperature effects on the development and stage-specific survival have been shown to influence both the quantity and quality of Tephritid fruit flies produced (Vargas *et al*., 1996; Vargas *et al*., 1997; Brévault and Quilici, 2000; Vargas *et al*., 2000; Duyck and Quilici, 2002; Trudgill *et al*., 2005; Grout and Stoltz, 2007; Rwomushana *et al*., 2008; Vayssières *et al*., 2008; Liu and Ye, 2009; Salum *et al*., 2013). Various Tephritid species have specific optimal temperature ranges for development that are limited by lower and upper thresholds. Development does not occur below and above these temperature limits and this can vary both with developmental stage and geographical origin (Honék and Kocourek, 1990). Information on the thermal requirements of insect groups forms an essential basis for understanding and predicting the geographical distribution of the different insect groups. This is the first study in which two linear and 26 nonlinear models have been used to model the effect of temperature on the development of this important fruit fly. The results will contribute to improve integrated pest management (IPM) programs.

Materials and Methods

Rearing methods

To establish and maintain the insect colony and conduct experiment, fruits infected with Mediterranean fruit fly were collected from citrus orchards in Mazandaran and Fars provinces. Infected citrus fruits were transferred to the growth chamber (in plastic boxes on sterilized sand) and phytotron (rearing of colony) at a temperature of 25 ± 1°C and 60 ± 10% RH and 16: 8 (L:D). Larvae and adults were reared for two generations on artificial food (bran, yeast, water, sugar, sodium benzoate and citric acid) and hydrolyzed protein in Petri dishes and large cylindrical containers (Mafi Pashaklai, 2013).

Experimental conditions

Rearing was conducted at (10, 12, 15, 17, 20, 25, 27, 30, 32, and 35 ± 1°C), 60 ± 5% RH, and a photoperiod of 16:8 (L:D) h in growth chambers. The environmental conditions of each phytotron were monitored with a temperature and relative humidity data logger.

Egg, Larval and Pupal development

Three hundred to 1000 eggs in groups of 100, less than one day old, on filter paper were incubated at 10, 12, 15, 17, 20, 25, 27, 30, 32, and 35 ± 1°C. All eggs were checked daily for hatching. The daily growth and development on artificial food and sterilized sand for larvae and pupae was monitored and recorded until the emergence of adult flies.

Developmental rate and mathematical models

Developmental rate is the reciprocal of developmental time in days. These rates are used in linear and nonlinear models where data are added daily (Arbab *et al*., 2006). Development is completed when the sum of daily developmental rate values equals 1 (Curry *et al*., 1978). Therefore, the integral of the developmental rate function over time can be used to simulate the development of an organism exposed to different temperatures (Arbab *et al*., 2006). The ordinary and Ikemoto linear and 26 nonlinear descriptive models were used to determine the relationship between temperature and Mediterranean fruit fly developmental rate. The parameters of interest are the lower and upper temperature thresholds (T_{min} and T_{max}, respectively), the optimal temperature (T_{opt}), and the thermal constant (K). Most models can estimate two or more parameters. In addition to the ordinary model, the Ikemoto linear model was used to obtain more reliable estimates of the lower temperature threshold and thermal constant (Ikemoto and Takai, 2000).

Three criteria including the sum of squared error (SSE), adjusted coefficient of determination (R^2_{adj}), and Akaike information criterion (AIC) were used to evaluate the nonlinear models. All nonlinear models in each stage were ranked using AIC, as the best statistical criterion (Akaike 1974), and the model with the smallest value of AIC was considered to be the best model for describing the temperature-dependent development of *C. capitata* According to Burnham et al. (2011), models with $\Delta > 7$ were dismissed where Δ is the difference between AIC of the best model and the i^{th} model. T_{fast}, the temperature that the maximum development rate occur was calculated directly from some of the nonlinear models (Arbabtafti *et al.* 2023). In addition to statistical criteria accuracy (Kontodimas *et al*. 2004), biological significance (Briere *et al*. 1999) were considered to select the best nonlinear model. The observed total development time of *C. capitata* in Mazandaran and Fars provinces was compared with those estimated using the selected nonlinear models.

Statistical Analysis of Developmental Rate

To determine the effect of different temperatures on the developmental time of the Mediterranean fruit fly, data were checked for normality. Then, one-way analysis of variance (ANOVA), was used to determine the significant differences in developmental time of total immature stages (from egg to pupal stage) at constant temperatures (Minitab, 2000). The differences among the treatments were compared using Tukey's test (α = 0.05). Comparison of development time of two provinces was done by the Student's t-test. Minitab (ver. 19.2) software was used for all analyses. Excel 2016 was used for graph construction. Evaluation of two linear and 26 nonlinear models was done by using Arthro Thermo Model (ATM) software (Mirhosseini *et al*. 2017) to describe the development rate (the reciprocal of development time) of *C. capitata* as a function of temperature. The ATM software calculates criteria and parameters for all models.

Results

Developmental Time

No development occurred at 10 and 12°C (in Fars province) and 10, 12, 15 and 17°C (in Mazandaran province). The mean developmental time of total immature stages (from egg to pupal stage) at ten constant temperatures in two provinces, is shown in Table 1. One-way ANOVA showed a significant effect of temperature on development time for total immature stages of Mediterranean fruit fly in Mazandaran and Fars provinces ($P < 0.05$). Total developmental time was extended at 15°C (52.50 d) and 20°C (26.01 d) in population of Mazandaran and Fars provinces, respectively.

Table 1. Developmental time of *Ceratitis capitata* total immature stages at ten constant temperatures.

Geographical population	Temperature (°C)	Total (day) Mean ± SE
Mazandaran	**10**	**-**
	12	**-**
	15	**52.50±0.5 ^{aA} N=2**
	17	**38.2±0.87 ^{bA} N=20**
	20	**20.11±0.28 ^{cB} N=70**
	25	**15.09±0.22 ^{dA} N=94**
	27	**13.30±0.12 ^{eA} N=121**
	30	**11.24±0.21 ^{defA} N=66**
	32	**-**
	35	**13±0.57^{defA} N=3**
	F	**632.27**
	df	**6,369**
	P	**0.000**
Fars	**10**	**-**
	12	**-**
	15	**-**
	17	**-**
	20	**26.01±0.17 ^{aA} N=121**
	25	**14.52±0.16 ^{bA} N=129**
	27	**13.39±0.10 ^{cA} N=133**
	30	**11.22±0.14 ^{dA} N=68**
	32	**-**
	35	**-**
	F	**1832.81**
	df	**3,447**
	P	**0.000**

Means followed by different lowercase letters in the columns are significantly different between different temperatures in each population (Tukey's test, $P < 0.05$) and the means followed with by capital letters were significantly different between two populations at each temperature (T-test, $P < 0.05$).

Model Evaluation

Linear models

Both linear models showed an acceptable fitness for total immature stages. The linear regression equation, the lower temperature threshold, and the thermal constant of the total immature stages of

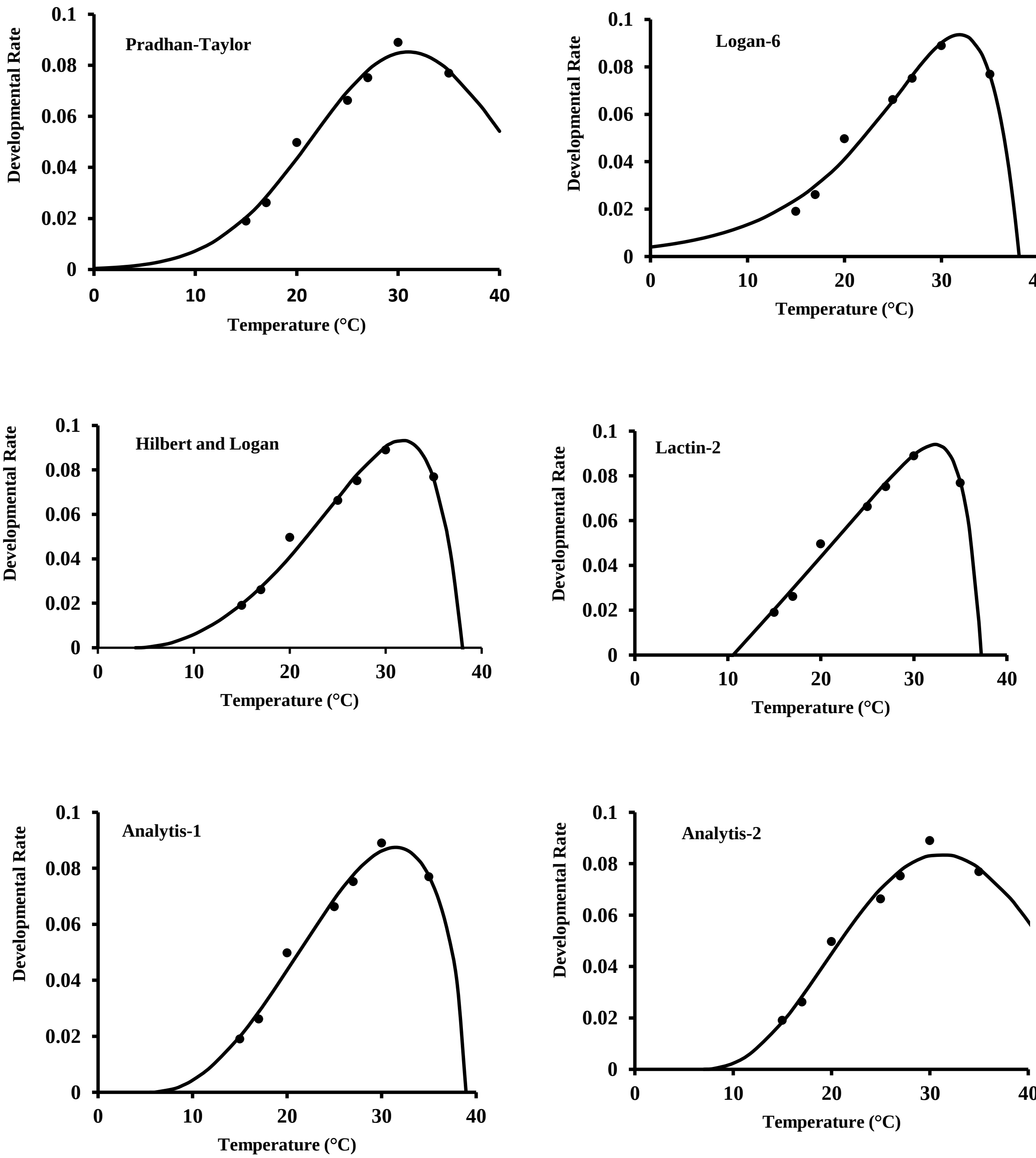
C. capitata are shown in Table 2. The Ikemoto linear model had a higher value of R^2 and R^2_{adj} than the ordinary model, indicating a slight degree of confidence in parameter estimates provided by the Ikemoto linear model. In addition to the ordinary model, the Ikemoto and Takai linear models were used to obtain more reliable estimates of the lower temperature threshold and thermal constant (Ikemoto and Takai 2000). The Ikemoto linear model estimated lower temperature thresholds for total developmental of *C. capitata* was 10.80 and 12.69 °C, in Mazandaran and Fars provinces, respectively. The thermal constant of total immature stages were 228.86 and 188.59 degree days (DD) in Mazandaran and Fars province, respectively.

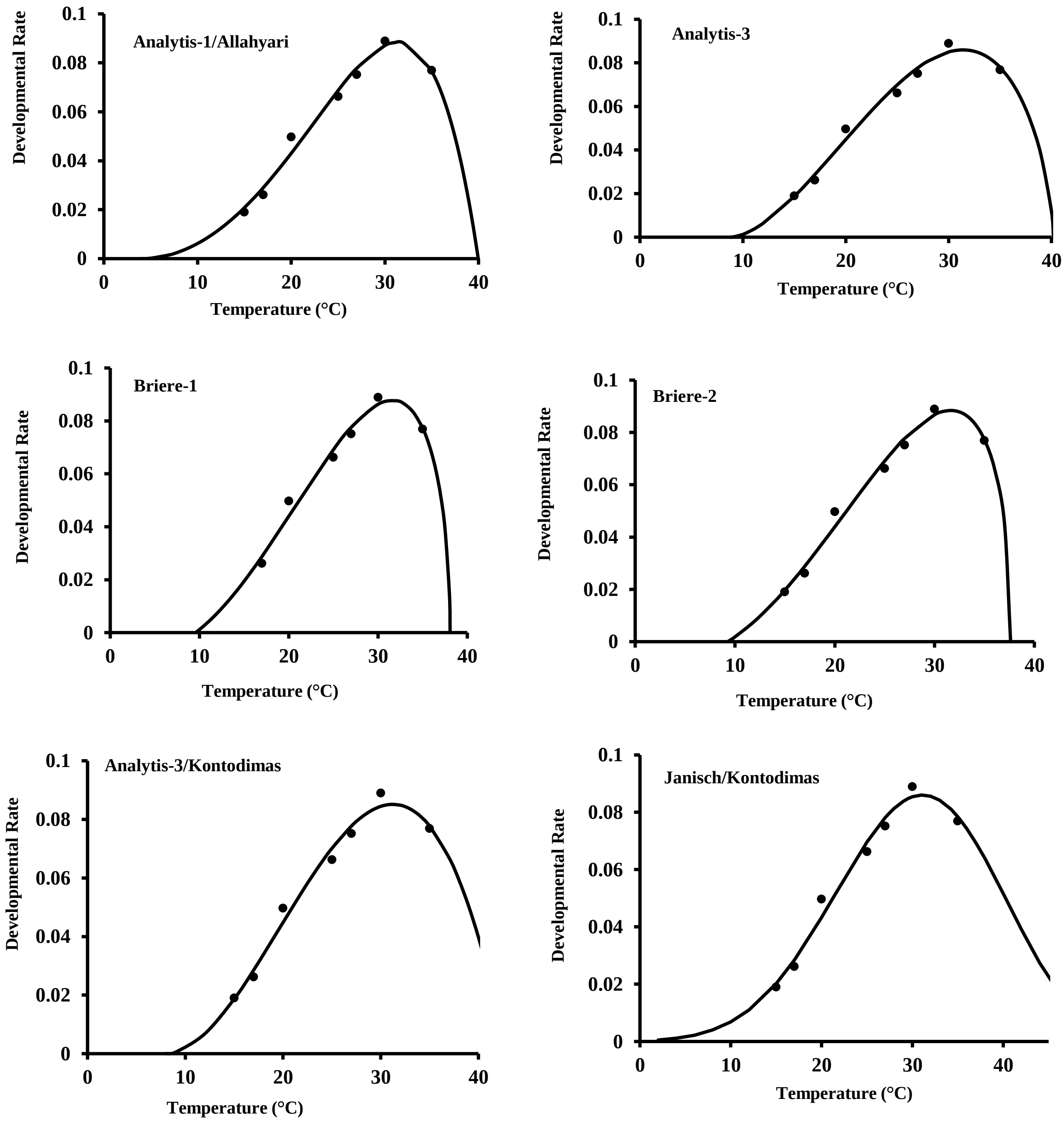
Table 2: Linear regressions, lower temperature threshold (T_{min}), and thermal constant (degree days) of *Ceratitis capitata* immature stages using two linear models.

Geographical population	Model	Stage	Linear equation	T_{min} (°C)	*K* (DD)	R^2	R^2_{adj}	*P*
Mazandaran	**Ordinary**	**Egg-pupa**	*R*= 0.024385+0.0033905T	7.1921	294.9416	0.84082	0.80898	0.003
	Ikemoto	**Egg-pupa**	*DT*= 228.8627+10.8028D	10.8028	228.8627	0.94398	0.93278	0.00007
Fars	**Ordinary**	**Egg-pupa**	*R*= 0.060777+0.0050415T	12.0553	168.3525	0.98692	0.98039	0.006
	Ikemoto	**Egg-pupa**	*DT*= 188.5943+12.695D	12.695	188.5943	0.99341	0.99011	0.0002

Nonlinear Models

The curve of the influence of temperature on the developmental rate of total immature stages (from egg to pupae stage) fitted by 18 models in the Mazandaran province (Figure 1) and five models in the Fars province is shown in Figure 2. The values of R^2, *RSS* (*SSE*), *AIC* (Akaike information criterion), and R^2_{adj} used to determine the goodness-of-fit, the models of the nonlinear models of the Mazandaran province are shown in Table 3. Considering the *AIC* and biological criteria (T_0, T_U, and T_{opt}) the Logan 6 model had the poorest and the Briere-1 model had the best fitness to data for total immature development in the Mazandaran province (Table 5). The values of measurable parameters of the nonlinear developmental rate models in Fars province are presented in Table 4. Among the non-linear models obtained from the Fars province, only the polynomial model was accepted for total immature development based on *AIC*, however biological criteria (T_0, T_U, and T_{opt}), it had the poorest ability to provide the growth and development model. Performance-2, and Briere-1 models have provided more accurate estimates for T_0, T_U, and T_{opt} in the Fars province (Table 6).


Pradhan-Taylor
Logan-6
Hilbert and Logan
Lactin-2
Analytis-1
Analytis-2
Developmental Rate
Temperature (°C)


Analytis-1/Allahyari
Analytis-3
Briere-1
Briere-2
Analytis-3/Kontodimas
Janisch/Kontodimas
Developmental Rate
Temperature (°C)
0
0.02
0.04
0.06
0.08
0.1
10
20
30
40

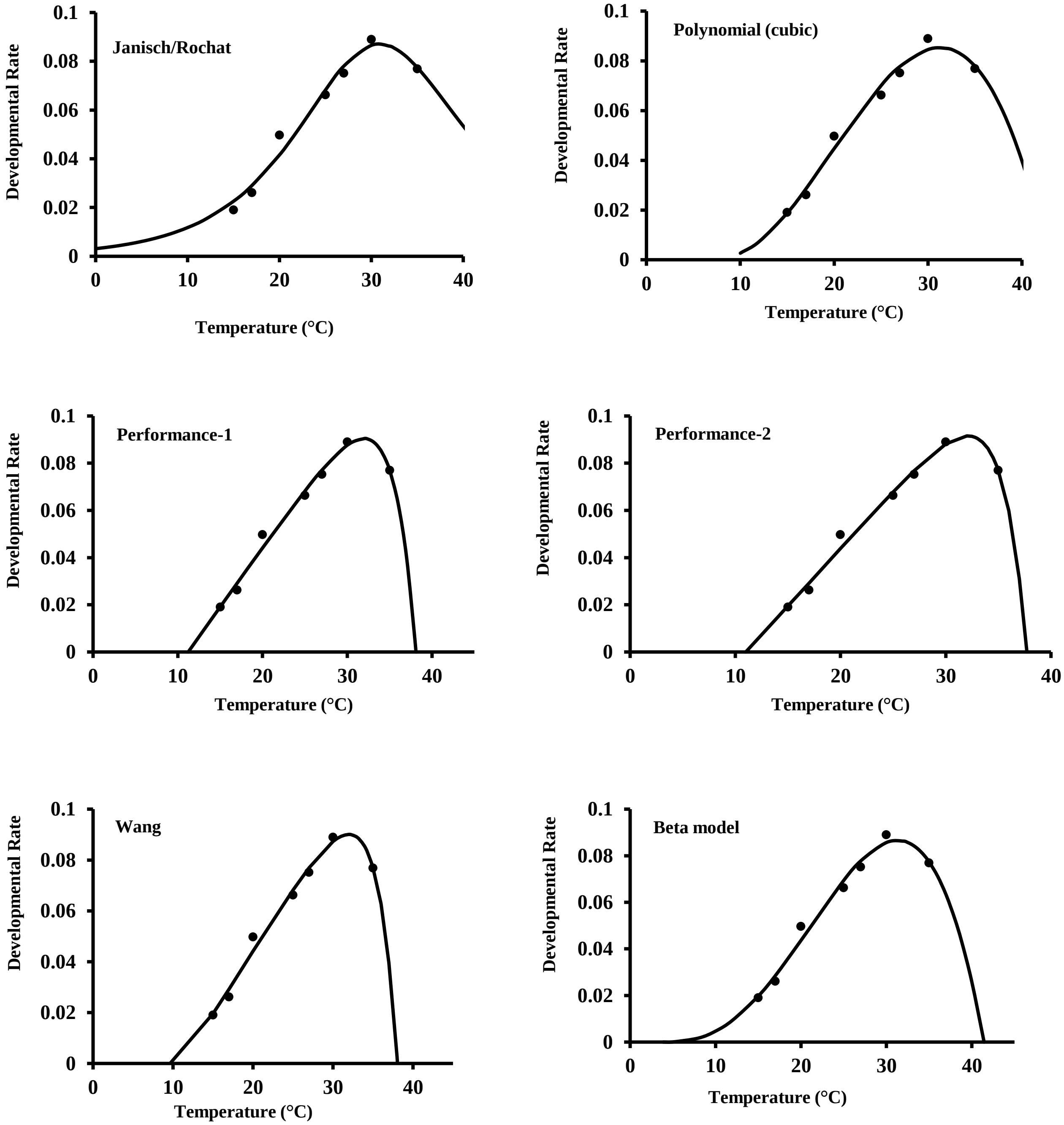


Figure 1. Observed development rate for total immature stages of Mazandaran province of *Ceratitis capitata* (dots) and 18 fitted nonlinear models (Lines).

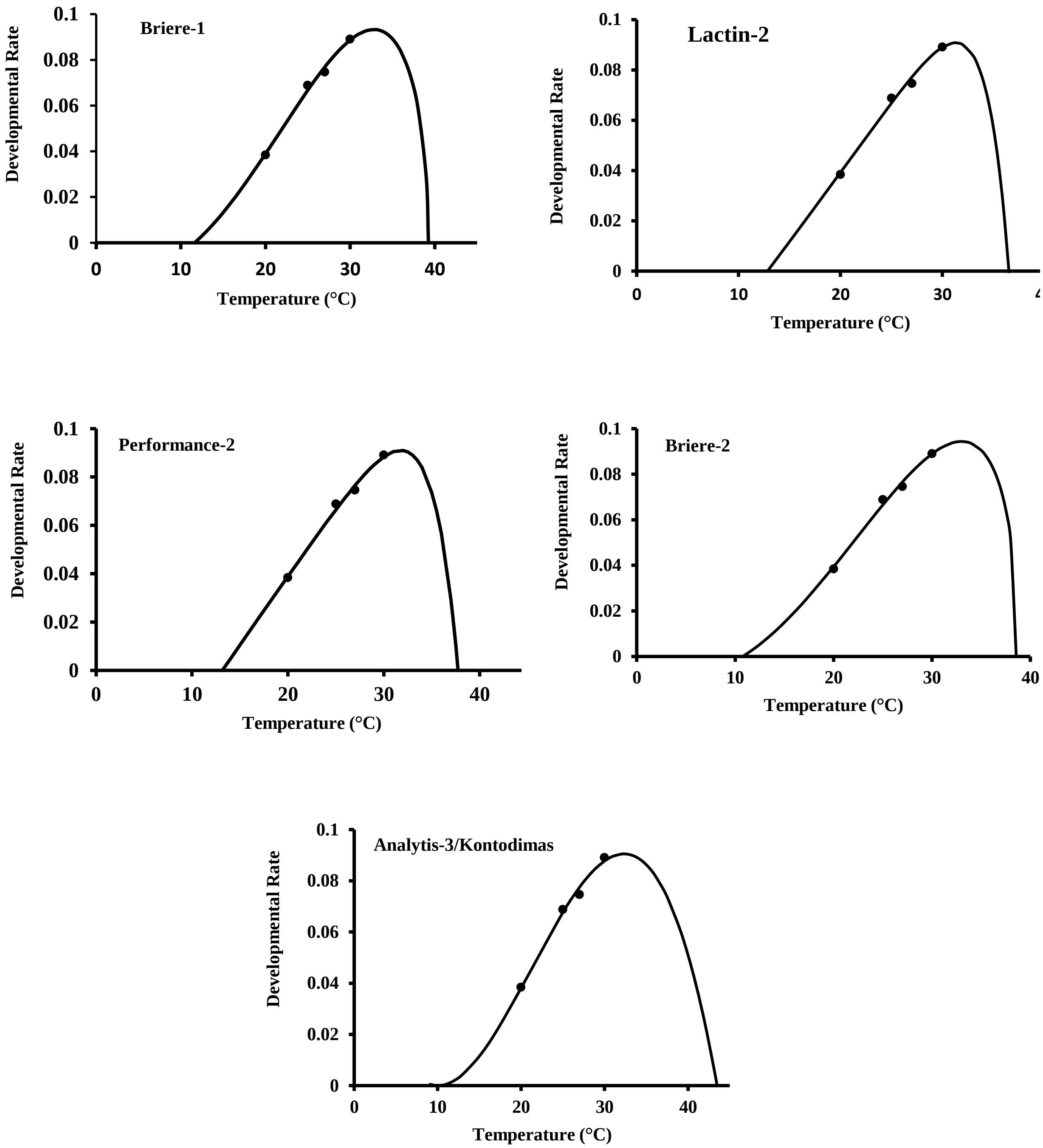


Figure 2. Observed development rate for total immature stages of Fars province of *Ceratitis capitata* (dots) and 5 fitted nonlinear models (Lines).

Table 3. Comparison of 26 developmental rate models based on the no. of parameters, *SSE*, Akaike information criterion (*AIC*), and adjusted R^2 (R^2_{adj}) for predicting egg, larva, pupa and total immature development stages of *Ceratitis capitata* in Mazandaran province

Model	No. of parameters	Total			
		SSE	R^2_{adj}	*AIC*	Rank[1]
Pradhan-Taylor	3	8.000005	0.9698	-73.1459	6
Davidsons logistic	3	0.0043	-0.4999	-45.8029	24
Logan-6	4	1.00004	0.9454	-69.0103	18
Hilbert and Logan	5	9.3209e-05	0.9346	-68.5861	19
Lactin-1	3	1.00004	0.9408	-68.4299	20
Lactin-2	4	5.000005	0.9752	-74.5425	3
Logan-10	5	9. 000005	0.9552	-68.3887	21
Analytis-1	5	6. 000005	0.9538	-71.0189	12
Analytis-2	5	8.000005	0.9414	-69.3496	17
Analytis-1/Allahyari	5	7. 000005	0.9498	-70.431	15
Analytis-3	5	6. 000005	0.9530	-70.8958	14
Briere-1	3	6.000005	0.9785	-75.5218	1
Briere-2	4	6.000005	0.9716	-73.5736	5
Analytis-3/Kontodimas	3	7.000005	0.9746	-74.3637	4
Janisch/Kontodimas	4	8.000005	0.9610	-71.3618	11
Janisch/Rochat	4	1.00004	0.9509	-69.747	16
Sharpe and DeMichele	7	0.0274	NaN[2]	-26.8023	26
Sharp and DeMichele/Schoolfield	7	0.0039	NaN	-40.4897	25
Sharp and DeMichele/Kontodimas	6	0.0013	-0.7976	-48.2395	23
Polynomial (cubic)	4	7.000005	0.9662	-72.3688	9
Sharpe–Schoolfield–Ikemoto (SSI model)	7	3. 000005	NaN	-71.4554	10
Performance-1	5	4.000005	0.9653	-73.0182	7
Performance-2	4	5.000005	0.9766	-74.9404	2
Wang	6	4.000005	0.9303	-70.9876	13
Ratkowsky	4	3.00004	0.9705	-61.6343	22
Beta`	4	7.000005	0.9669	-72.5221	8

1 Rank is based on the *AIC* criteria.
2 NAN The number of model parameters is equal to or greater than the observations and cannot be calculated Model - Data could not be fitted by the model.

Table 4. Comparison of 26 developmental rate models based on the no. of parameters, *SSE*, Akaike information criterion (*AIC*), and adjusted R^2 (R^2_{adj}) for predicting total immature development of *Ceratitis capitata* in Fars province.

Model	No. of parameters	Total			
		SSE	R^2_{adj}	*AIC*	Rank[1]
Pradhan-Taylor	3	0.00001	0.9763	-45.3017	3
Davidsons logistic	3	0.0014	-1.9999	-25.9319	13
Logan-6	4	0.00001	NaN[2]	-41.6177	10
Hilbert and Logan	5	-	-	-	-
Lactin-1	3	0.00001	0.9647	-43.7057	5
Lactin-2	4	0.00001	NaN	-43.3518	8
Logan-10	5	-	-	-	-
Analytis-1	5	-	-	-	-
Analytis-2	5	-	-	-	-
Analytis-1/Allahyari	5	-	-	-	-
Analytis-3	5	-	-	-	-
Briere-1	3	0.000009	0.9791	-45.7944	2
Briere-2	4	0.00001	NaN	-43.5121	7
Analytis-3/Kontodimas	3	0.00001	0.9749	-45.0691	4
Janisch/Kontodimas	4	0.0015	NaN	-23.6038	14
Janisch/Rochat	4	0.00001	NaN	-40.8527	11
Sharpe and DeMichele	7	-	-	-	-
Sharp and DeMichele/Schoolfield	7	-	-	-	-
Sharp and DeMichele/Kontodimas	6	-	-	-	-
Polynomial (cubic)	4	0.0000	NaN	-227.7655	1
Sharpe–Schoolfield–Ikemoto (SSI model)	7	-	-	-	-
Performance-1	5	-	-	-	-
Performance-2	4	0.00001	NaN	-43.5767	6
Wang	6		-	-	-
Ratkowsky	4	0.00004	NaN	-37.9192	12
Beta`	4	0.00001	NaN	-43.2408	9

1 Rank is based on the *AIC* criteria
2 NAN The number of model parameters is equal to or greater than the observations and cannot be calculated Model
- Data could not be fitted by the model.

Table 5. Values of fitted coefficients and measurable parameters of 18 developmental rate models to describe immature stage development of the *Ceratitis capitata* in Mazandaran province.

Model	Parameter	Value
Pradhan-Taylor	r_m	0.08524 (0.07732, 0.09316)
	T_{opt} (°C)	31
	$T\sigma$ (°C)	9.459 (7.418, 11.5)
Logan-6	Δ_T	4.99 (-27.04, 37.02)
	ψ	0.004267 (-0.00202, 0.01055)
	ρ	0.1296 (-0.4758, 0.735)
	T_{max} (°C)	38.01 (31.58, 44.44)
	T_{opt} (°C)	31.9
Hilbert and Logan	D	56.45 (-1.123e+05, 1.124e+05)
	Δ_T	3.526 (-62.35, 69.41)
	ψ	0.5187 (-2048, 2049)
	T_{min} (°C)	3.911 (-112.4, 120.3)
	T_{max} (°C)	40 (-140.6, 220.6)
	T_{opt} (°C)	31.72
Lactin-2	Δ	1.929 (-4.485, 8.344)
	λ	-1.047 (-1.08, -1.015)
	ρ	0.00435 (0.002843, 0.005857)
	T_{min} (°C)	10.59
	T_{max} (°C)	41.55 (20.71, 62.39)
	T_{opt} (°C)	32.3
Analytis-1	P	0.3931 (-11.38, 12.16)
	m	0.6314 (-14.28, 15.54)
	n	2.2 (-29.77, 34.17)
	T_{min}(°C)	5.52 (-142.3, 153.3)
	T_{max}(°C)	38.93 (-58.59, 136.4)
	T_{opt} (°C)	31.09
Analytis-2	P	3.286e+05 (-4.495e+12, 4.495e+12)
	m	2.735 (-25.89, 31.35)
	n	4.132 (-3.505e+06, 3.505e+06)
	T_{min} (°C)	6.376 (-94.12, 106.9)
	T_{max} (°C)	55.92 (-39.66, 151.5)
	T_{opt} (°C)	31.09
Analytis-1/Allahyari	P	0.2319 (-6.458, 6.922)
	m	4 (-96.35, 104.4)
	n	2.038 (-54.85, 58.92)
	T_{min} (°C)	3.903 (-328, 335.8)
	T_{max} (°C)	39.97 (12.65, 67.29)
	T_{opt} (°C)	
Analytis-3	a	9.417e-05 (-0.0102, 0.01039)
	m	0.6681 (-14.83, 16.17)
	n	1.72 (-17.79, 21.23)
	T_{min} (°C)	8.793 (-72.46, 90.05)
	T_{max} (°C)	40.2 (-84.11, 164.5)
	T_{opt} (°C)	31.09
Briere-1	a	4.951e-05 (3.529e-05, 6.373e-05)
	t_{min} (°C)	9.553 (6.264, 12.84)
	T_{max} (°C)	38.07 (36.43, 39.7)
	T_{opt} (°C)	31.9

Briere-2	a	5.522e-05 (-0.0001026, 0.0002131)
	n	2.192 (-3.56, 7.945)
	T_{min} (°C)	9.267 (-0.188, 18.72)
	T_{max} (°C)	37.62 (25.82, 49.42)
	T_{opt} (°C)	31.64
Analytis-3/Kontodimas	a	1.351e-05 (6.226e-06, 2.08e-05)
	T_{min} (°C)	7.963 (5.177, 10.75)
	T_{max} (°C)	42.87 (39.27, 46.47)
	T_{opt} (°C)	31.23
Janisch/Kontodimas	D_{min}	4.968 (0.4977, 9.439)
	k	0.0742 (-0.2308, 0.3792)
	λ	0.05016 (-0.06608, 0.1664)
	T_{opt} (°C)	34.25 (-13.09, 81.58)
Janisch/Rochat	C	0.08659 (0.05224, 0.1209)
	a	1.116 (0.7389, 1.492)
	b	1.143 (0.9574, 1.328)
	T_{max} (°C)	30.06 (10.85, 49.28)
	T_{opt} (°C)	30.9
Polynomial (cubic)	a_0	-1.372e-05 (-4.413e-05, 1.669e-05)
	a_1	0.000812 (-0.001498, 0.003122)
	a_2	-0.01055 (-0.06684, 0.04575)
	a_3	0.04067 (-0.3963, 0.4777)
	T_{min} (°C)	
	T_{max} (°C)	42.849
	T_{opt} (°C)	31.3
Performance-1	C	2.162 (-474.5, 478.8)
	$K1$	0.002354 (-0.5263, 0.531)
	$K2$	0.3431 (-3.903, 4.59)
	T_{min}(°C)	11.23 (-3.707, 26.17)
	T_{max}(°C)	38.1 (14.27, 61.92)
	T_{opt} (°C)	31.94
Performance-2	$K2$	0.3956 (-0.8109, 1.602)
	m	0.004867 (0.002948, 0.006786)
	T_{min}(°C)	10.99 (7.62, 14.36)
	T_{max}(°C)	37.71 (30.48, 44.93)
	T_{opt} (°C)	32.071
Wang	C	0.2473 (-68.09, 68.59)
	$K1$	0.001469 (-14.51, 14.51)
	$K2$	0.3611 (-75.46, 76.18)
	m	3.15 (-3.069e+04, 3.07e+04)
	T_{min}(°C)	9.626 (-89.9, 109.2)
	T_{max}(°C)	38.06 (-284.2, 360.3)
	T_{opt} (°C)	31.97
Beta	r_m	0.08657 (0.07226, 0.1009)
	T_{min}(°C)	3.865 (-35.25, 42.98)
	T_{max}(°C)	41.44 (31.5, 51.38)
	T_{opt} (°C)	31.29 (29.23, 33.35)

Table 6. Values of fitted coefficients and measurable parameters of 5 developmental rate models to describe total immature stage development of the *Ceratitis capitata* in Fars province.

Model	Parameter	Value
Lactin-2	Δ	-
	λ	-
	ρ	-
	T_{min} (°C)	-
	T_{max} (°C)	-
	T_{opt} (°C)	-
Analytis-3	a	-
	m	-
	n	-
	T_{min} (°C)	-
	T_{max} (°C)	-
	T_{opt} (°C)	-
Briere-1	a	5.284e-05 (-0.0001954, 0.0003011)
	t_{min} (°C)	11.61 (-21.42, 44.65)
	T_{max} (°C)	39.25 (-21.12, 99.62)
	T_{opt} (°C)	32.81
Briere-2	a	6.26e-05
	n	2.383
	T_{min} (°C)	10.78
	T_{max} (°C)	38.57
	T_{opt} (°C)	33.01
Performance-2	$K2$	0.3271
	m	0.005697
	T_{min}(°C)	13.15
	T_{max}(°C)	37.74
	T_{opt} (°C)	31.8

Discussion

Determining the developmental time at different temperatures is necessary to calculate the developmental rate. The present findings in Mazandaran province was different from the results of Ricalde *et al*. (2012) and Grout and Stoltz, 2007 at similar temperatures. Therefore, Ricalde *et al*. (2012), obtained the most extended period of developmental time of total immature stages of *C.capitata* was 71.20 d. at 15°C and the shortest, 16.90 d. at 30°C. Furthermore, Grout and Stoltz, (2007) reported that the longest developmental time of total immature stages of *C.capitata* at 14°C was 83.6 d. and the shortest, 21.2 d. at 30°C. The differences in the obtained results can be caused by regional climatic variability (e.g., temperature, humidity and rainfall), which can affect the development and survival of *C. capitata* populations (Papadogiorgou *et al*., 2024). Linear models only estimate a lower temperature threshold, and this is proper for analysis of the phenology of insect populations due to simplifying the analysis (Ikemoto & Kiritani, 2019).

In the present study, lower temperature thresholds and thermal constant were estimated using both ordinary and Ikemoto linear models. A comparison of total developmental time at different temperatures showed that the linear range was up to 30°C for the population of Mazandaran and Fars provinces. The R^2_{adj} coefficients used to fit the regression between temperature and the developmental rate were higher for the Ikemoto linear model on the two populations tested.

The lower temperature threshold for total immature stages was estimated by the Ikemoto linear model at 10.80 °C and 12.69°C, for the Mazandaran and Fars provinces, respectively. The lower temperature threshold values estimated by Ricalde *et al.* (2012) (9.10, 9.30, 9.60°C) and Grout and Stoltz (2007) (9.9°C) are closer our result of Mazandaran province. Based on Honek and Kocourek (1990) T_0 decreased if K increased therefore, the thermal constant of total immature stages of *C. capitata* for the two linear ordinary and Ikemoto linear models were obtained at 294.94 and 228.86 degree days in Mazandaran province, while it was 168.35 and 188.59 degree days In Fars province, respectively. The result reported by Grout and Stoltz (2007) 337.8 (DD), and Ricalde *et al*. (2012) 350, 341 and 328 (DD) were higher than our results.

Many abiotic factors affect the growth and development of insects. Temperature is the most significant environmental factor influencing insect development, survival, behavior, and distribution (Fletcher, 1989). Biological parameters like developmental zero and the thermal constant are supposed to be the limiting factors in the geographic distribution of fruit flies (Ye, 2001). The developmental response of insects to temperature can help to predict their occurrence and, therefore, assist in monitoring and control strategies for pests. Different species of Tephritidae have particular optimal temperature ranges for development, which are limited by low and high thresholds (Honék and Kocourek, 1990). Different temperature characteristics, may be affected by pest species (Honek, 1999), pest population (Lee and Elliott, 1998), growth, and development stages (Honek, 1996; Kocourek and Stara, 2005) and other ecological factors such as food source (Golizadeh *et al*., 2007), and interspecies and intraspecies competition (Duyck and Quilici, 2004) and the difference may be due to one or a set of the above factors. Model selection is critical because of the significant differences between model predictions. Rebaudo and Rabhi (2018) point out each of the criteria for model selection has its advantages and disadvantages therefore, a combination of different methods should be used in model selection, e. g. the *AIC* criteria can separate several models with the same R^2_{adj} and *SSE*. In most studies, the *AIC* index has been mentioned as the best statistical parameter to measure the validity of models furthermore, model selection should be performed based on observations and biological and ecological information or biological significance (Arbabtafti *et al.* 2023). A standard method for evaluating the accuracy of estimated critical temperatures is based on their comparison with experimental data (Kontodimas *et al*., 2004).

Conclusions

The findings of this study especially in relation to temperatures, can be used to accurately predicting *C.capitata* population development in different provinces and enable us to choose the best time for controlling this pest. Since the development rate of *C.capitata* may be influenced by factors such as host plants of *C.capitata*, further studies should be done on different host plants to obtain the best development models.

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رشد نمو وابسته به دما و آستانه‌های دمایی کل مراحل نابالغ مگس میوه مدیترانه‌ای، *Ceratitis capitata* (Wiedemann, 1824) (Diptera: Tephritidae) در ایران

نجمه ابراهیمی

چکیده

مگس میوه مدیترانه‌ای ((Diptera: Tephritidae) (Wiedemann, 1824) *Ceratitis capitata* یکی از مهمترین آفات محصولات کشاورزی مناطق گرمسیری و نیمه‌گرمسیری جهان است. در این پژوهش نرخ رشد و نمو مگس میوه مدیترانه‌ای در دماهای 10، 12، 15، 17، 20، 25، 27، 30، 32، 35 درجه سلسیوس بررسی شد. یافته‌های حاصل وجود رابطه غیرخطی بین دما و نرخ رشد و نمو را نشان داد. از بین مدل‌های غیر خطی، مدل پرفورمانس-1 و پرفورمانس-2 به ترتیب در دو استان مازندران و فارس بیشترین برازش را روی مقادیر مشاهده شده نرخ رشد و نمو را نشان دادند. در استان مازندران، مدل پرفورمانس -1 ضمن شبیه سازی نزدیک به واقعیت رشد و نمو مگس میوه مدیترانه‌ای در گستره دمایی 15 تا 35 درجه سلسیوس، دمای بهینه رشد و نمو کل دوره نابالغ مگس میوه مدیترانه‌ای را 31/94 درجه سلسیوس برآورد کرد و همچنین در استان فارس مدل پرفورمانس-2، در گستره دمایی 20 تا 30 درجه سلسیوس، دمای بهینه رشد و نمو کل دوره نابالغ مگس میوه مدیترانه‌ای را 31/8 درجه سلسیوس برآورد کرد. دمای آستانه پایین برای رشد و نمو کل دوره نابالغ مگس میوه مدیترانه‌ای در استان مازندران با استفاده از مدل پرفورمانس -1، 11/23 و در استان فارس با استفاده از مدل پرفورمانس-2، 13/15 درجه سلسیوس برآورد شد. دمای آستانه بالا نیز برای رشد و نمو کل مراحل نابالغ مگس میوه مدیترانه‌ای در استان مازندران با استفاده از مدل مدل پرفورمانس -1، 38/1 درجه سلسیوس و در استان فارس مدل پرفورمانس-2، 37/74 درجه سلسیوس، تخمین زده شد. در بین مدل‌های خطی مورد بررسی، مدل خطی ایکیموتو توانست دمای آستانه پایین و نیاز دمایی مراحل مختلف نابالغ مگس میوه مدیترانه‌ای را با دقت بیشتری برآورد نماید.