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Life table and development parameters of green peach aphid [*Myzus persicae* (Sulzer) (Hemiptera: Aphididae)] at six different temperatures on pepper (*Capsicum annuum* L.)

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Abstract: The green peach aphid *Myzus persicae* (Sulzer) (Hemiptera: Aphididae) is an essential pest of pepper (*Capsicum annuum* L.). This study was conducted in 2015–2016. In this study, we collected data using 1 linear and 6 non-linear temperature-dependent development models, development parameters, and a life table of *M. persicae* at 6 different temperatures (18 °C, 22 °C, 25 °C, 28 °C, 30 °C, and 32 °C) on pepper. The development threshold temperature was 3.9 °C, and the thermal constant was 174.0 degree/day. The minimum, optimum, and maximum growth temperatures were calculated as 14.27 °C, 27.5 °C, and 35.5 °C, respectively. The shortest growth period of *M. persicae* was found to be 8.14 days at 28°C. The raw data obtained at the end of the study were analysed according to the age-stage, two--sex life table method. The highest intrinsic rate of increase (*r*) and the highest finite rate of increase (λ) were 0.25 d^{-1} and 1.28 d^{-1} at 25 °C, respectively. The highest net reproductive rate (*R0*) was 61.64 nymphs/female at 22 °C, and the highest mean generation time (*T*) was 20.92 days at 18 °C. According to the models applied, the optimum temperature for pest development is 27.5 °C, but the intrinsic rate of increase (*r*) calculated from the life table parameters was statistically higher in the 22 °C and 25 °C test groups. In this study, we investigated the effect of temperature on the pest's growth and development. Based on the observations, the temperatures at which the plants were not negatively affected and the insect's activity was limited, were determined from the reproduction, development, and life table parameters obtained under different temperatures in this study. This information may help effectively control pests without using, or minimise the use of, pesticides and emphasise the temperature factor, especially in places such as greenhouses where controlled climatic conditions are provided.

Keywords: population projection; temperature-dependent development models; age- stage; two-sex life table

Pepper (*Capsicum annuum* L.) is one of the most economically important agricultural products used in every field, from food to health. Approximately 38 mil. t of pepper are produced worldwide each year (FAO 2019), and Turkey accounts for a significant share of global production, with an annual output of 2.97 mil. t (TUIK 2021).

The green peach aphid, *Myzus persicae* (Sulzer) (Hemiptera: Aphididae), is an important pest of pepper and feeds on more than 400 hosts across

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about 40 families. It carries more than 100 plant viruses (Blackman & Eastop 1984). *M. persicae* can reach very dense populations by sucking the sap from young leaves, stems, buds, and flowers of the plant (Bass et al. 2014). Pesticides are generally used to control the polyphagous *M. persicae*. Excessive use of pesticides not only harms beneficial organisms and humans but also causes outbreaks of other pests. Therefore, environmentally friendly practices should be adopted in the control methods (Cuthbertson & Murchie 2003). In agricultural areas, integrated pest management is particularly important for controlling this pest.

The use of temperature factors, genetically resistant plants, and similar methods is an ecological and economic approach suitable for integrated pest management of *M. persicae* (Goundoudaki et al. 2003; Atlihan & Özgökçe 2004; Akköprü et al. 2015). In pest control, when using the temperature factor, which affects insect survival activities such as development, reproduction, and nutrition, the appropriate temperature can be selected by considering the temperature tolerance of the agricultural production plant (Özgökçe et al. 2018).

Insects develop normally at optimal temperatures, whereas development and reproductive rates decrease when temperatures are excessively high or low (Andrewartha & Birch 1954). When temperature conditions are extreme, aphid survival and respiration are adversely affected (Lamb 1961). The number of temperature studies on aphids, especially on *M. persicae*, has increased significantly in recent years. In particular, effective results have started to be obtained in studies investigating the possibilities of using high temperatures that plants can tolerate for short or normal periods against *M. persicae*, and it has become clear that these studies, which are few, should be carried out more (Baral et al. 2022; Khurshid et al. 2022; Saleesha et al. 2022). Life tables are useful tools for making comprehensive comparisons across studies with different conditions, such as temperature and variety. The minimum, optimum, and maximum development temperatures of the pests were calculated using different temperature models. In this study, different models were used to obtain the minimum, optimum, and maximum temperatures at which the insects can thrive and their performance at each temperature was evaluated with life table parameters generated at different temperatures and temperature-dependent growth thresholds under constant temperature regimes were estimated using the Logan model (Logan et al. 1976) modified by Lactin et al. (1995). Although life table parameters are obtained in some studies, there are very few in which different temperatures and models are used with them. It is believed that data from life tables and temperature models can contribute to pest control. The current study can be used to develop targeted strategies to prevent green peach aphid by providing insight into how different constant temperatures affect the reproduction, development, and life table parameters of *M. persicae.* It is very important to reduce pesticide use and its toxic effects on the environment and living things. This study aims to demonstrate, based on the aforementioned data, that a healthy control can be carried out against this pest in areas such as greenhouses and seedlings where controlled climatic conditions are provided, without using chemicals or minimising the use of temperature as a control against *M. persicae.*

MATERIAL AND METHODS

Plant cultivation

The experiment used the Amiral pepper (*C. annuum* L.) variety, one of the most widely used pepper varieties in Turkey. In previous preliminary studies, the Amiral pepper variety, which was the most resistant to pests among 5 pepper varieties (Amiral, Erciyes, Mert, Mertcan, and Naz), was used in the trial. The host plant was grown in 4-litre plastic pots in a climate room. The climate room was set to 25 °C, 60% humidity, and 16 : 8 light : dark conditions.

Aphid production

The green peach aphid (*M. persicae*) used in the experiment was obtained from the Süleyman Demirel University Department of Plant Protection, Biological Control Laboratory, and cultured in a climate chamber. To maintain colony cleanliness, clean plants were produced in weekly cycles and replaced old plants that began to collapse. At least three generations were grown on the Amiral pepper variety to break the telescoping effect before the aphid was included in the experiment.

The studies were carried out in climate chambers and climate rooms set at 6 different temperatures (18 °C, 22 °C, 25 °C, 28 °C, 30 °C, and 32 °C ± 1 °C),

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60 ± 5% relative humidity, and 16 : 8 light : dark conditions. The present study examined the effects of temperature on aphid development. One adult aphid was transferred to Plexiglas clip cells measuring 2 cm in diameter and 2 cm in height, weighing 1.8 ± 0.2 g, and covered with muslin cloth. The next day, all individuals except one of the nymphs were removed from the cell. The developmental stages of the nymphs and the number of offspring per day were counted and removed through daily observations. Observations were recorded until the aphid died. For each temperature study, 4–5 pots were used, 10–12 leaf cells were attached to each pot, and the experiments were carried out with 50 replications.

Temperature-dependent development models

A total of 7 models, 1 linear and 6 non-linear, were used to predict the temperature-dependent growth of *M. persicae* (Campbell et al. 1974; Obrycki & Tauber 1982; Kontodimas et al. 2004).

Linear model

The thermal constant (*K*) and development threshold (*C*) can be estimated only by the linear equation (Campbell et al. 1974; Obrycki & Tauber 1982; Kontodimas et al. 2004).

$$d(T) = a + bt \tag{1}$$

$$K = \frac{1}{b} \tag{2}$$

$$C = \frac{-a}{b} \tag{3}$$

Where: $d(T)$ – the rate of development at temperature T (°C) – days^{-1}; a and b – constants.

Non-linear models

Polynomial (4th)

$$y = a + bx + bx^2 + dx^3 + ex^4 \tag{4}$$

Logan-6. (Logan et al. 1976; Logan 1988)

$$d(T) = \psi\left[e^{\rho T} - e^{\left(\rho T_{max} = \frac{T_{max}-t}{\Delta}\right)}\right] \tag{5}$$

Where: $d(T)$ – the development rate at temperature T (°C) – days^{-1}; ψ – the maximum development rate; Δ – the temperature range in which physiological deterioration becomes dominant; ρ – a constant defining the rate of optimal temperature; T_{max} – the high temperature threshold.

Logan-10. (Logan et al. 1976; Logan 1988)

$$d(T) = \alpha\left[\frac{1}{1 + ke^{-\rho.T}} - e^{\left(\frac{Tmax-T}{\Delta}\right)}\right] \tag{6}$$

Where: α, κ – experimental constants; ρ, T_{max}, Δ – the same as the Logan 6 model.

Janisch. (Janisch 1932)

$$d(T) = \frac{T_{min}}{2}\left[e^{k(T-T_{opt})} + e^{-\lambda(T-T_{opt})}\right] \tag{7}$$

Where: T_{min} – the low-temperature; T_{opt} – the optimum temperature; λ, k – the empirical constants.

Lactin-1. (Tsai & Liu 1998; Brie're & Pracros 1999)

$$d(T) = e^{\rho - T} - e^{\left(\rho T_{max} - \frac{T_{max}-T}{\Delta}\right) + \lambda} \tag{8}$$

Where: *ρ*, T_{max}, Δ – see the Logan 6 model, λ forces the curve to intercept the *y*-axis at a value below zero, allowing the estimation of a low-temperature threshold.

Briere-1. (Brie're & Pracros 1998)

$$d(T) = \alpha T(T - T_{min})\sqrt{T_{max} - T} \tag{9}$$

Where: T – the rearing temperature (°C); α – an empirical constant; T_{min} –a low development threshold temperature; T_{max} – the lethal temperature threshold.

Life table study and analysis

The raw data obtained in the study, in which *M. persicae* on Amiral pepper variety at 6 different constant temperatures (18 °C, 22 °C, 25 °C, 28 °C, 30 °C and 32 °C ± 1 °C) were analysed with TWOSEX-MSChart (Chi 1988; Chi & Liu 1985; Huang & Chi 2011).

Age- stage-specific survival rate (s_{xj}, x – age, j – stage), age-specific survival rate (l_x), age-specific fecundity (m_x), as well as population parameters; the intrinsic rate of increase (r), the finite rate of increase (λ), the net reproductive rate (R_0), the mean generation time(T), life expectancy (e_{xj}), reproductive value (v_{xj}), population doubling time (DT) and gross reproduction rate (GRR) were calculated according to the following formulas:

$$l_x = \sum_{j=1}^{k} s_{xj} \tag{10}$$

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$$m_x = \frac{\sum_{j=1}^{m} s_{xj} f_{xj}}{\sum_{j=1}^{m} s_{xj}} \quad (11)$$

The intrinsic rate of increase (r) is calculated using the Euler-Lotka formula.

$$\sum_{x=0}^{\infty}\left(e^{-r(x+1)}\sum_{j=1}^{m} s_{xj} f_{xj}\right) = \sum_{x=0}^{\infty} e^{-r(x+1)} l_x m_x = 1 \quad (12)$$

The net reproductive rate (R_0) (Birch 1948).

$$R_0 = \sum_{x=0}^{\infty}\sum_{j=1}^{m} s_{xj} f_{xj} = \sum_{x=0}^{\infty} l_x m_x \quad (13)$$

For each individual, life expectancy (e_{xj}) for age (x) and period (j) is calculated according to Chi and Su (2006).

$$e_{xj} = \sum_{i=x}^{\infty}\sum_{y=j}^{\beta} s'_{iy} \quad (14)$$

The mean generation time (T) (Birch 1948; Carey 1993):

$$T = (ln\ R_0)/r \quad (15)$$

The finite rate of increase (λ) (Birch 1948; Fathipour & Maleknia 2016):

$$\lambda = e^r \quad (16)$$

Reproductive value (v_{xj}) (Carey 1993):

$$v_{xj} = \frac{e^{r(x+1)}}{s_{xj}}\sum_{i=x}^{\infty} e^{-r(i+1)}\sum_{y=j}^{\beta} s'_{iy} f_{iy} \quad (17)$$

Doubling time (Birch, 1948):

$$DT = \frac{ln}{rm} \quad (18)$$

Where: rm – intrinsic rate of increase.

Gross reproduction rate: (Carey 1993):

$$GRR = \sum m_x \quad (19)$$

Population projection

Using life table data, the population size of green peach aphid (*M. persicae*) was estimated with the computer program Timing-MSChart, following the method reported by Chi and Liu (1985) and Chi (1990). The computer program TIMING-MSChart (version 2021) was used to estimate the population size of 10 nymphs at the end of 60 days, based on life table parameters (Chi 2021).

P(t) – population projection of the insect as follows:

$$P(t) = \sum_{j=1}^{m}\left(\sum_{x=0}^{\infty} c_{xj} n_{xj,t}\right) \quad (20)$$

In this method, when a certain number of individuals in a certain period are taken as the initial population of green peach aphids, the size that the population can reach at the end of the specified period can be estimated based on age (x) and period (j) specific and total number of individuals.

RESULTS

Effect of temperature on total development times and reproduction values

It was observed that different temperatures affected all stages of *M. persicae*. In the study, 2-winged aphids were observed at 18 °C and 22 °C. When the pre-adult duration of the pest was analysed, it decreased until 30 °C and then increased again at 32 °C. The reproductive period of the pest ranged from 1.40 to 27.08 days. When the total pre-reproductive period was analysed, it was found to be equal to the total development period, since the adult pre-reproductive period was zero (0) at all temperatures. Adult longevity was longest at 18 °C with 35.44 days and shortest at 32 °C with 2.6 days. Although survival rates were quite high at temperatures below 30 °C, they were observed to be low at 30 °C and 32 °C, respectively. The longest pre-adult durations were recorded as 13.1 days at 32 °C and 12.38 days at 18 °C, followed by 9.55 days at 22 °C, 8.27 days at 25 °C, 8.14 days at 28 °C, and 8.47 days at 30 °C. The population doubling times (DTs) of *M. persicae* at 18 °C, 22 °C, 25 °C, 28 °C, and 30 °C were calculated as 3.66, 2.98, 2.78, 3.23, and 6.39 days, respectively. The population doubling time could not be calculated at 32 °C because individuals did not complete development (Table 1).

Effects of temperature on life table parameters

When the life table parameters were examined, it was observed that the net reproductive rate (R_0) of the *M. persicae* decreased with increasing temperature, the highest values were found as 61.64 and 52.34 offspring at 22 °C and 18 °C, and statistically different rates of 32.45, 16.62, 3.38

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Table 1. Reproduction, longevity, survival rates and development parameters (mean ± SE) of *Myzus persicae* on Amiral pepper variety at six different temperatures

Nymphal duration (d)	Temperatures					
	18 °C (*n* = 50)	22 °C (*n* = 50)	25 °C (*n* = 50)	28 °C (*n* = 50)	30 °C (*n* = 50)	32 °C (*n* = 50)
1st Instar	4.58 ± 0.23[a]	3.16 ± 0.14[b]	2.18 ± 0.09[b]	2.84 ± 0.11[c]	1.62 ± 0.07[c]	2.00 ± 0.13[d]
2nd Instar	2.52 ± 0.19[b]	2.46 ± 0.19[b]	1.98 ± 0.09[c]	2.10 ± 0.16[bc]	1.30 ± 0.08[d]	3.30 ± 0.20[a]
3rd Instar	1.88 ± 0.14b[c]	2.30 ± 0.17[ab]	1.91 ± 0.10[c]	1.86 ± 0.12[c]	1.92 ± 0.14[bc]	2.92 ± 0.29[a]
4th Instar	3.38 ± 0.19[a]	1.59 ± 0.26[c]	2.20 ± 0.17[b]	1.33 ± 0.11[c]	3.86 ± 0.30[a]	4.40 ± 1.60[abc]
Pre-adult duration	12.38 ± 0.24[a]	9.55 ± 0.36[b]	8.27 ± 0.26[c]	8.14 ± 0.18[c]	8.47 ± 0.32[c]	13.00 ± 1.67[a]
Adult longevity	35.44 ± 2.26[a]	31.20 ± 1.76[a]	20.86 ± 0.99[b]	14.92 ± 0.54[c]	7.36 ± 0.71[d]	2.60 ± 0.93[e]
Total longevity	46.34 ± 2.39[a]	40.16 ± 1.71[b]	29.14 ± 0.89[c]	22.78 ± 0.60	14.12 ± 0.60	10.24 ± 0.46
Survival rate	0.998[a]	0.999[a]	0.999[a]	0.997[a]	0.964[b]	0.860[c]
Reproduction						
APRP*	0	0	0	0	0	0
TPRP**	12.38 ± 0.24[a]	9.55 ± 0.36[b]	8.27 ± 0.26[c]	8.14 ± 0.18[c]	8.50 ± 0.32[c]	13.00 ± 1.67[a]
Reproductive days	25.04 ± 1.38[a]	27.08 ± 1.47[a]	15.55 ± 1.03[b]	10.06 ± 0.45[c]	3.56 ± 0.42[d]	1.40 ± 0.24[e]
Fecundity (nymphs/female)	54.52 ± 2.98[a]	62.90 ± 3.62[a]	32.45 ± 3.09[b]	16.96 ± 1.07[c]	4.69 ± 0.64[d]	2.20 ± 0.97[e]
Doubling time	3.66 ± 0.06[b]	2.98 ± 0.06[d]	2.78 ± 0.09[d]	3.23 ± 0.10[c]	6.39 ± 1.04[a]	–7.12 ± 4.13[e]

n – number of individual; APRP* – adult pre-reproductive period; TPRP** – total pre-reproductive period; means in the same row followed by different letter are significantly; different (paired bootstrap test at 5% level); standard error

and 0.22 offspring were recorded at 25 °C, 28 °C, 30 °C and 32 °C, respectively. The highest value of the intrinsic rate of increase (r) was 0.25 d^{-1} at 25 °C. The highest mean generation time (T) was observed at 18 °C, with a value of 20.92 days. The finite rate of increase (λ) was 1.28 d^{-1} at 25 °C, followed by 1.26 d^{-1} at 22 °C, 1.24 d^{-1} at 28 °C, 1.21 d^{-1} at 18 °C, 1.11 d^{-1} at 30 °C and 0.9 d^{-1} at 32 °C (Table 2).

Temperature-dependent development models

Linear growth was observed from 18 °C to 25 °C, ceased at 28 °C, and resumed from 30 °C to 32 °C. While linear regression was applied to the 18–25 °C range where linear growth occurred, Polynomial (4th), Logan 6, Logan 10, Lactin 1, Briere 1, and Janish models were applied to all temperature values (Figure 1). The growth threshold (C) and temperature constant (K) of the pest were calculated by the

Table 2. Life table parameters (mean ± SE) of *Myzus persicae* on Amiral pepper variety at six different temperatures

Parameters	Temperatures					
	18 °C	22 °C	25 °C	28 °C	30 °C	32 °C
Ro (offspring/individual)	52.3400 ± 3.2000[a]	61.6400 ± 3.7400[a]	32.4500 ± 3.0500[b]	16.6200 ± 1.0900[c]	3.3800 ± 0.5400[d]	0.2200 ± 0.1300[e]
r (d^{-1})	0.1892 ± 0.0031[c]	0.2328 ± 0.0047[a]	0.2496 ± 0.0086[a]	0.2144 ± 0.0064[b]	0.1084 ± 0.0150[d]	–0.0973 ± 0.0059[e]
λ (d^{-1})	1.2083 ± 0.0038[c]	1.2621 ± 0.0059[a]	1.2835 ± 0.0110[a]	1.2391 ± 0.0079[b]	1.1145 ± 0.0167[d]	0.9072 ± 0.0496[e]
T (days)	20.9200 ± 0.2900[a]	17.7000 ± 0.2900[b]	13.9400 ± 0.2700[c]	13.1100 ± 0.2700[d]	11.2300 ± 0.2600[e]	15.5600 ± 1.3200[b]

Means in the same row followed by different letter are significantly different (paired bootstrap test at 5% level); R_0 – net reproductive rate; r – intrinsic rate of increase; λ – finite rate of increase; T – mean generation time * means in the same line fallowed by the same letter represent no significant difference between parameters (Bootstrap, P <0.05); standard errors were measured by 100 000 bootstrap resampling

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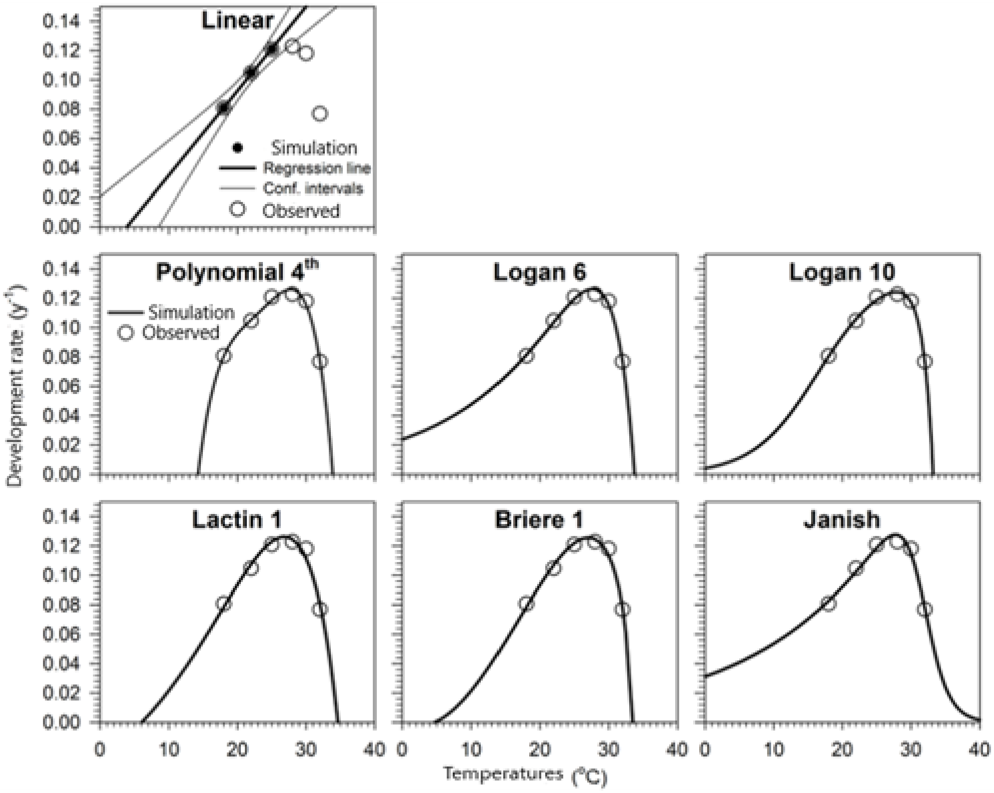

Figure 1. Different temperature models projection of *Myzus persicae*

linear regression method. Accordingly, the development threshold was found to be "3.90 °C" and the temperature constant to be "173.97 degree- days". The lowest (t_{min}) and highest (t_{max}) growth temperatures, which negatively affect pests, and the best (t_{opt}) temperatures at which it can survive were obtained theoretically from non-linear models or temperature curves. The lowest growth temperatures were determined by Polynomial (4th), Lactin 1 and Briere 1 models and recorded as 4.69 °C, 6.50 °C and 14.0 °C, respectively. The highest growth temperatures were determined by all models except Janish and recorded as 33.50 °C, 34.19 °C, 33.27 °C, 35.95 °C, and 33.13 °C, respectively. The best growth temperature was determined by all models and recorded as 27.50 °C, 27.60 °C, 29.50 °C, 29.50 °C, 29.50 °C, 29.00 °C, and 31.60 °C, respectively. The fit criteria for the curves were determined according to the lowest *AICC* and the highest R^2. The correlation coefficient was quite high across all models, ranging from 97.7% to 99.7% (Table 3).

Survival rate, age-stage specific fecundity and maternity

The curves (s_{xj}) show in detail the survival rates of *M. persicae* at different temperatures, in each period (1–4th instar nymph, adult), depending on age and stage. Transitions between periods and their durations, it was observed that at high temperatures (30 °C and 32 °C), large decreases were observed in the survival rates in the pre-adult and adult periods (Figure 2). When the total survival rates (l_x) of the pest are analysed, it is seen that it changes with the increase in temperature and the survival rate is extremely low at 32 °C. At other temperatures, the survival rate decreases due to ageing, especially at the end of the adult period. When the Maternity curve ($l_x m_x$), which is known as the reproductive curve, is examined, it changes in parallel with the reproductive rate curve changed in parallel with the reproductive rate, since individuals at all temperatures except 28 °C and 32 °C remain alive until about half of their lifespan (Figure 3).

Reproductive value

The reproductive value (v_{xj}), which reflects an individual's contribution to the future population at any age and stage (Carey 1993; Fisher 1999), was evaluated in detail for both pre-adult and adult stages of *M. persicae* at different temperatures on the experimental Amiral pepper variety.

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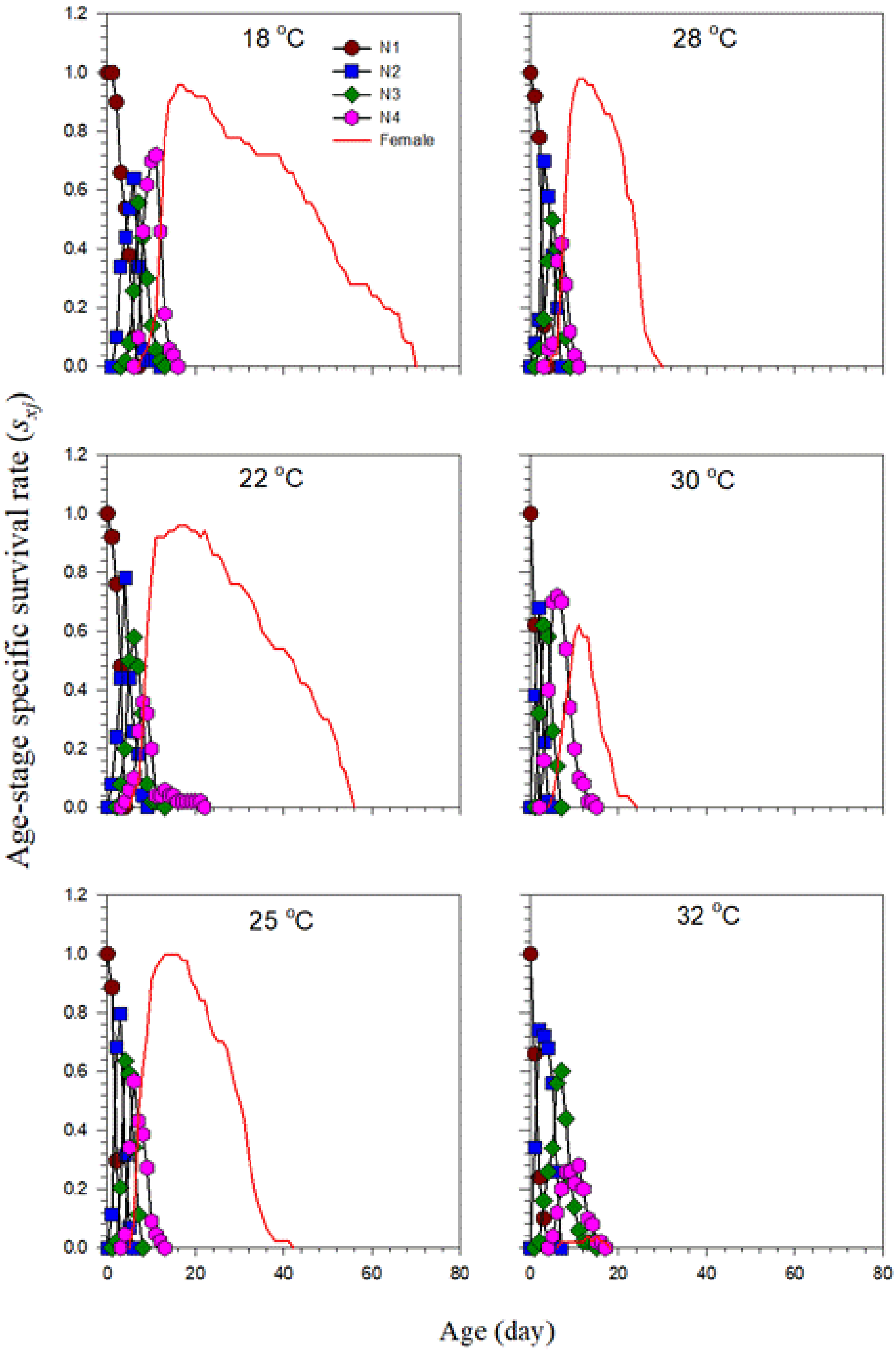

Figure 2. Age- stage dependent (s_{xj}) survival rates of *Myzus persicae* at 6 different temperatures

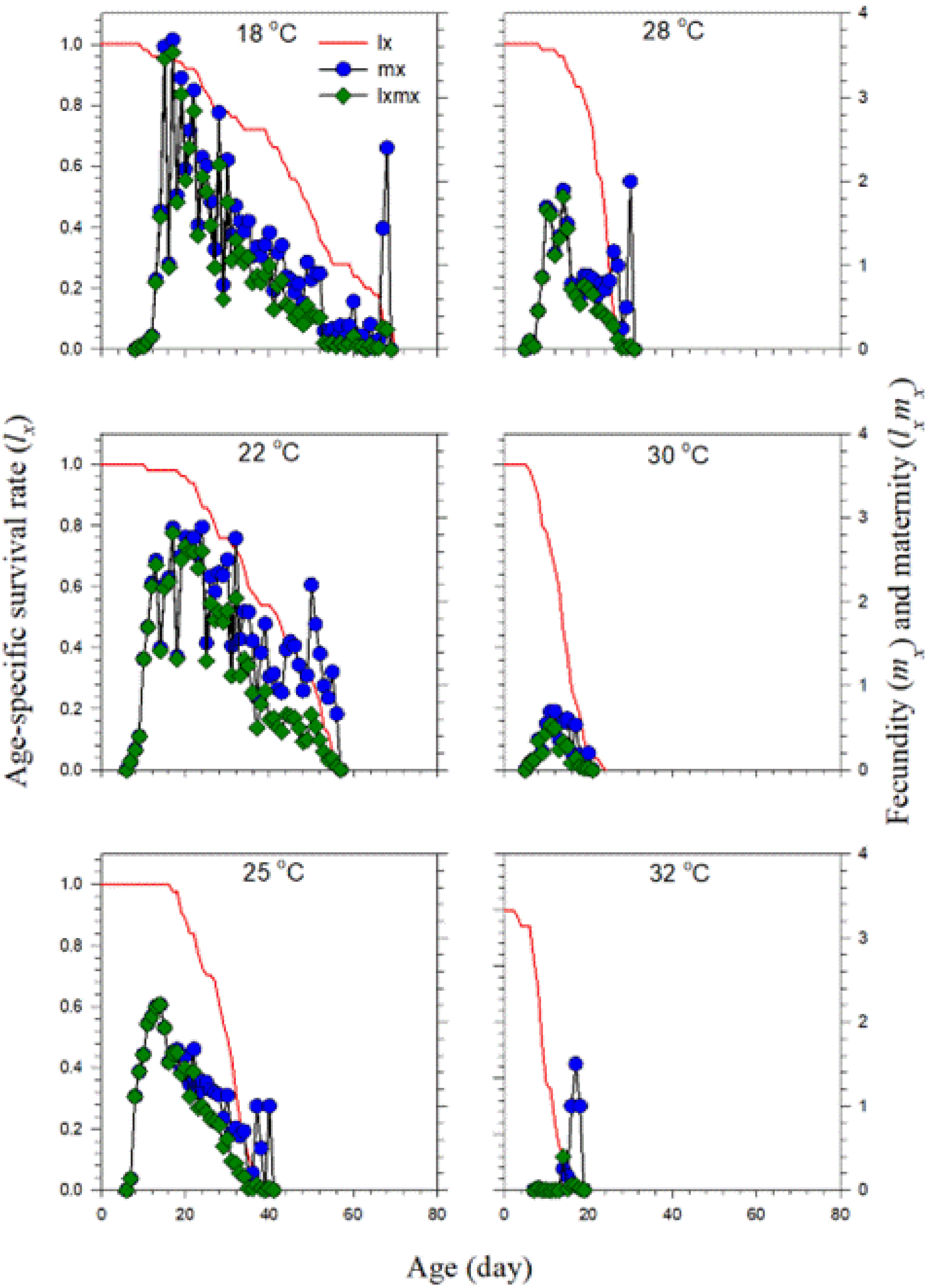

Figure 3. Age-specific survival rate (l_x), female age-specific fecundity (m_x) and age-specific maternity ($l_x m_x$) curves of *Myzus persicae* at 6 different temperatures

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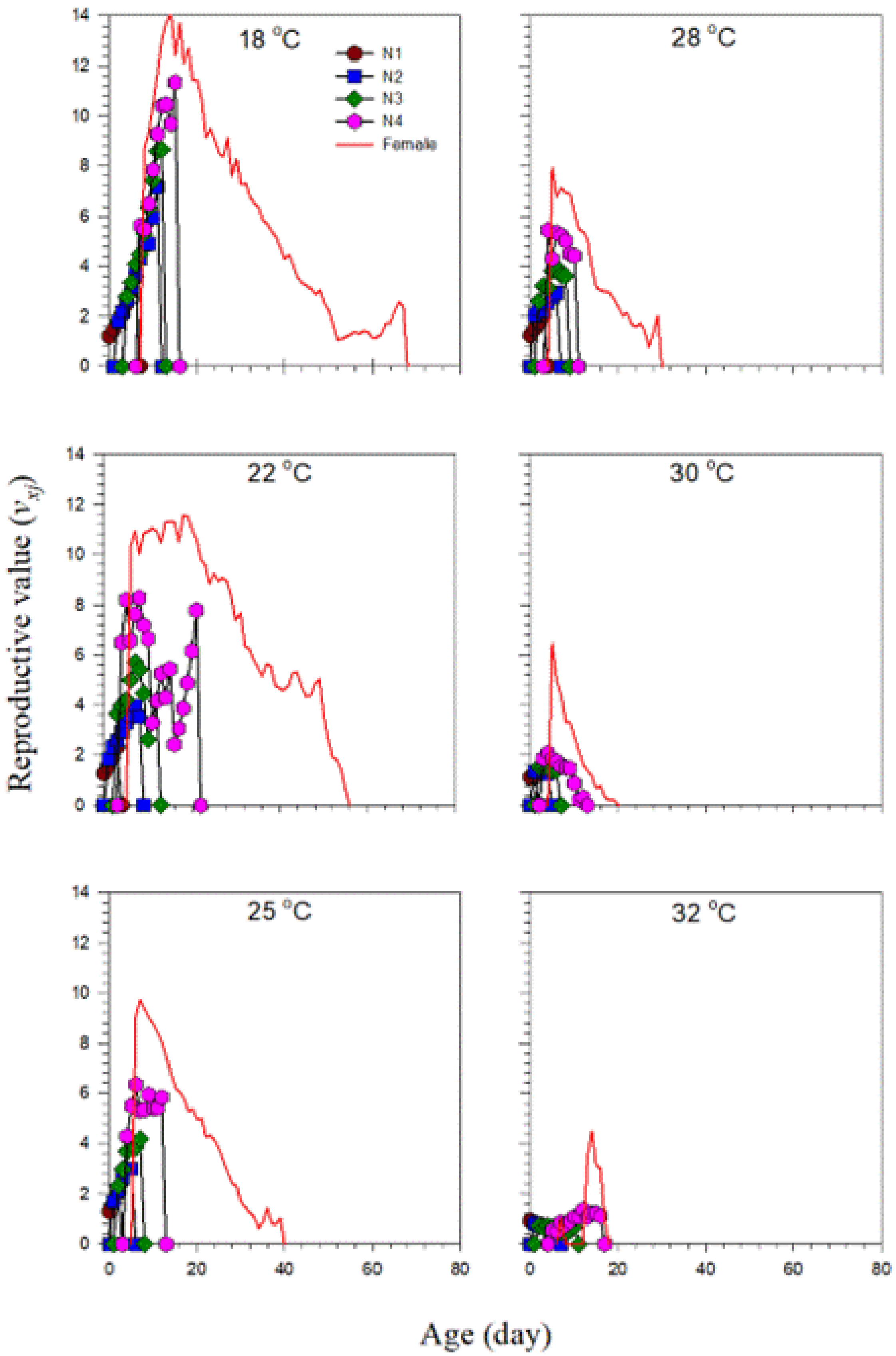

Figure 4. Age-stage specific reproductive value of *Myzus persicae* at 6 different temperatures and age- stage dependent reproduction curves (v_{xj})

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Table 3 linear and non-linear parameters of different models

Model		Total development	Model		Total development
Linear	a	−0.02 ± 0.04			
	b	0.06 ± 0.002			
	K	173.97			
	C	3.90			
	R^2	0.999			
	$AICC$	−39.99			
Polynomial (4th)	a	−3.40 ± 3.66	Lactin 1	λ	−0.06 ± 0.02
	b	0.60 ± 0.61		ρ	0.01 ± 0.06
	c	−0.04 ± 0.04		Δ	9.11 ± 4.49
	d	0.001 ± 0.00		t_{min^*}	6.5
	e	−1.20E-05 ± 0.00		t_{opt^*}	29.5
	t_{min^*}	14.00		t_{max}	35.95 ± 4.01
	t_{opt^*}	27.50		R^2	0.962
	t_{max^*}	33.50		$AICC$	−49.40
	R^2	0.989			
	$AICC$	−26.99			
Logan 6	Ψ	0.06 ± 0.020	Briere 1	a	0.0001 ± .000010
	P	0.14 ± 0.01		t_{min}	4.69 ± 1.67
	Δ	6.08 ± 0.74		t_{opt^*}	29.00
	t_{opt}	27.6		t_{max}	33.13 ± 0.16
	t_{max}	34.19 ± 0.53		R^2	0.981
	R^2	0.982		$AICC$	−63.48
	$AICC$	−53.66			
Logan 10	A	0.14 ± 0.02	Janish	D_{min}	11.56 ± 1.21
	K	32.45 ± 43.90		k	0.54 ± 0.14
	P	0.21 ± 0.01		t_{opt}	31.60 ± 0.44
	t_{opt^*}	29.50		λ	0.01 ± 0.012
	t_{max}	33.27 ± 0.45		R^2	0.977
	Δ	1.43 ± 0.58		$AICC$	−52.36
	R^2	0.997			
	$AICC$	−32.88			

* Obtained from the graphs; *a* and *b* are temperature constants

It was observed that productivity decreased with increasing temperature, with the highest productivity at 18 °C (Figure 4). However, according to the intrinsic rate of increase parameter, the value calculated at 18 °C is statistically lower than those calculated at 22 °C and 25 °C.

Life expectancy

When the graphs of the life expectancy (e_{xj}) calculated as a function of the survival rate of the pest are examined; it is seen that it decreases smoothly at 18 °C, 22 °C, and 25 °C, but the life expectancy curve does not decrease smoothly with the increase in survival rate and shortening of adult longevity at 28 °C, 30 °C, 32 °C due to increasing temperature (Figure 5).

Population projection

The number of individuals that 10 newborn nymphs of *M. persicae* could produce at the end of 60 days under different temperature conditions was estimated by the TIMING package program for each developmental stage (Figure 6). At the end of this period, when calculated according to the

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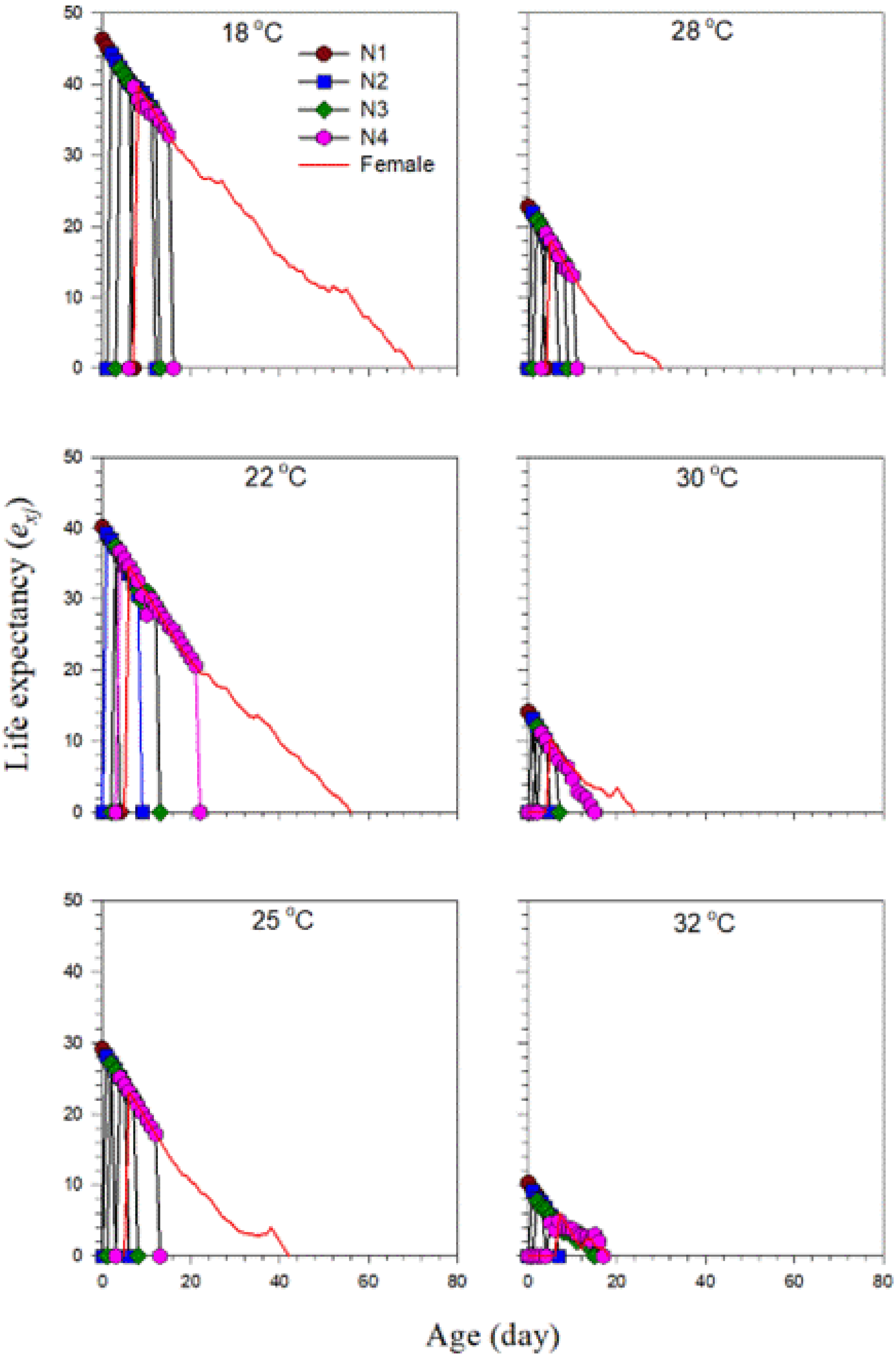

Figure 5. Life expectancy (e_{xj}) of *Myzus persicae* at 6 different temperatures

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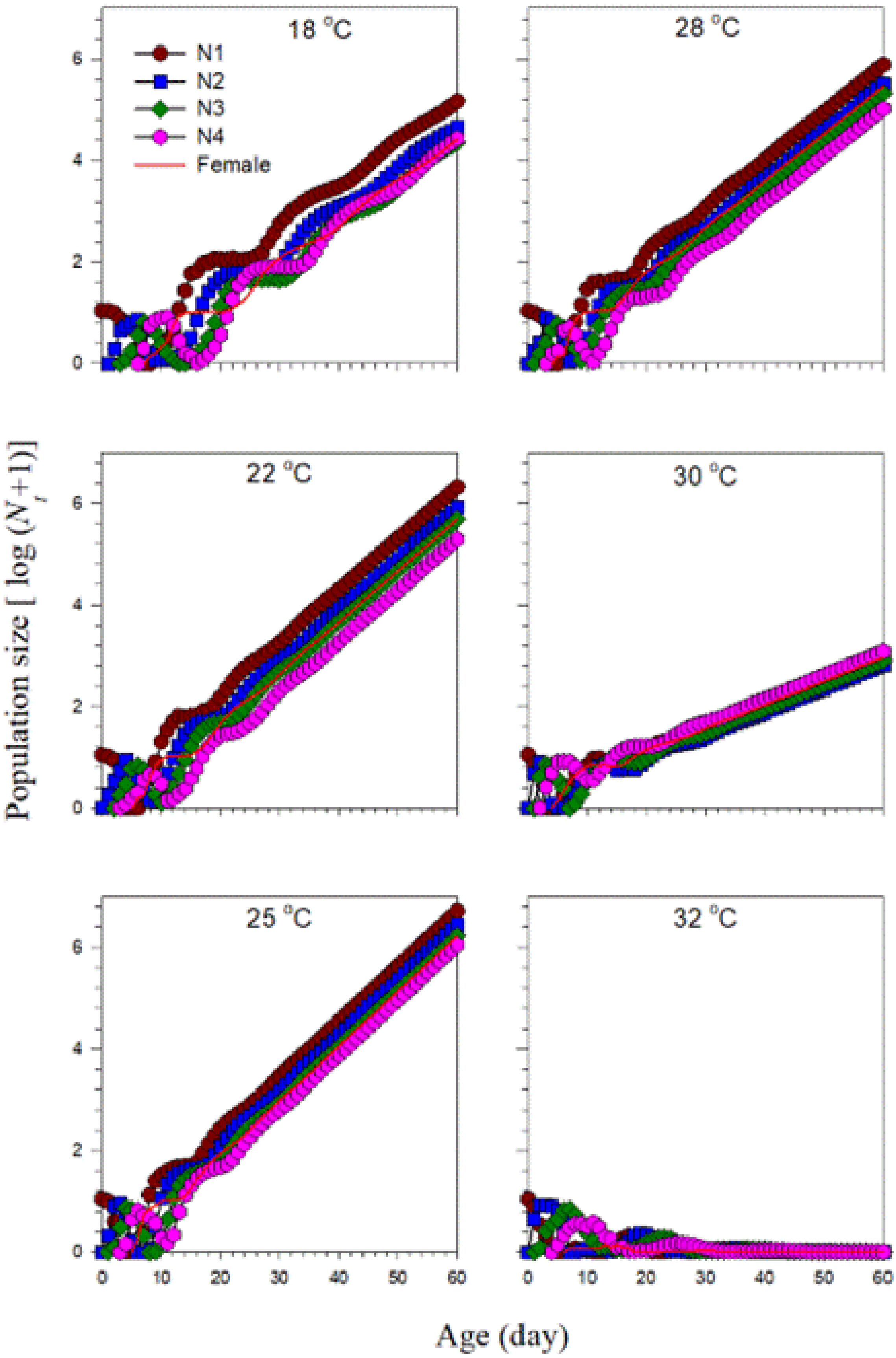

Figure 6. Population projection of *Myzus persicae* at the end of 60 days (all stages) (log+1) (TIMING)

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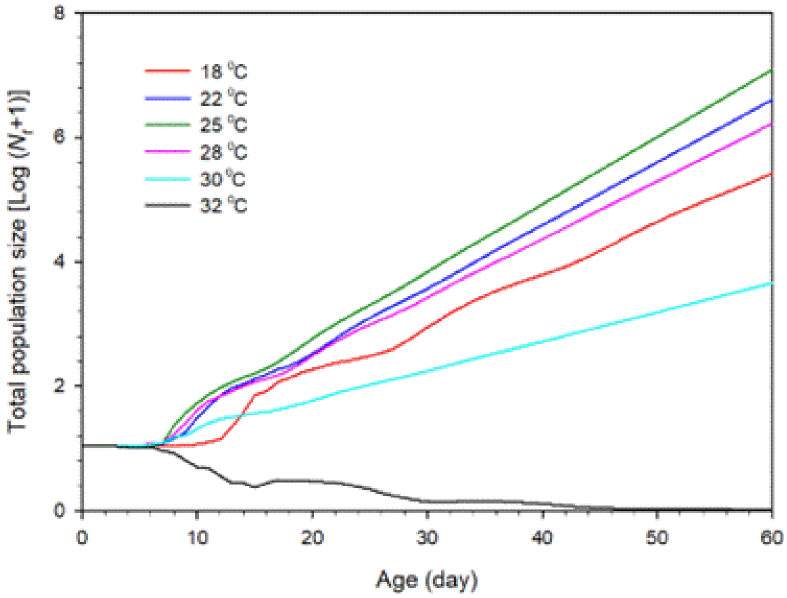

Figure 7. Total population size of *Myzus persicae at the* end of 60 days at 6 different temperatures

sum of all stages, the total number of individuals is estimated to reach 6 938, 3 724, 2 654, 897, 174, 174, 0.4 individuals at 25 °C, 22 °C, 28 °C, 18 °C, 20 °C, 32 °C, respectively. Looking at the graphs generated from this information, it was observed that the pest reached the highest number of individuals at 25 °C (Figure 7).

DISCUSSION

Studies on green peach aphid (*M. persicae*) have been conducted at different temperatures. In this study, different temperatures were used to determine the effects of temperature on the survival and behaviour of *M. persicae* and to explore their use in pest management applications. Since insects have a variable body temperature (Poikilothermal), temperature changes significantly affect all life parameters, from feeding to reproduction (Neven 2000). The development of *M. persicae* is negatively affected at 30 °C, and linear development ceases (Kim et al. 2012). It was observed that the pest showed linear development at temperatures between 18 °C and 25 °C; development ceased at 28 °C, and development regressed at 30–32 °C. Some life table parameters, such as fecundity, development, and the intrinsic rate of increase, vary with temperature. Although values such as reproductive rate and net reproductive capacity are high at 18 °C and 22 °C, this difference is due to the much longer development time at low temperatures. A study was made on the effects of constant temperatures on the development and fecundity of *M. persicae* fed on Brussels sprouts leaf discs (Din 1976). The nymphal development rate increased with temperature change from 10–29 °C. Fecundity was highest at 25 °C and decreased at 28 °C, and decreased progressively at 30 °C and 32 °C. The intrinsic rate of increase was calculated for the different temperatures and was highest at 25 °C (Din 1976). In the above study, the highest intrinsic rate of increase and fecundity were found at 25 °C, whereas in our study, the intrinsic rate of increase was highest at 25 °C. Still, fecundity was highest at 22 °C (Tables 1 and 2). Since temperature and cultivar effects affect all parameters, they provide a precise assessment of the growth rate of any insect pest population (Tuan et al. 2016). They can thus be used to determine the tolerance level of any host plant to insect herbivores (Güncan & Gümüş 2017). Katsarou et al. (2005) briefly exposed *M. persicae* on pepper and eggplant leaves to these high temperatures for 1 h at 30 °C, 2 h at 35 °C, and 4 h at 40 °C, respectively, and measured their development time. Short-term high temperatures had little effect on survival activities. In our study, we observed that constant high temperatures shortened development time to a certain degree, but above 30 °C, development time began to increase again (Table 1).

The parameter *r* (intrinsic rate of increase) is widely used in demographic analyses of insect populations (Birch 1948). This parameter (*r*) summarises an insect's physiological capacity to increase and is

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often used to compare the fitness of populations across diverse climatic and food-related conditions (Tsai & Wang 2001; Saeed et al. 2010). Different temperatures affect the parameter *r*. It is seen that this parameter is quite low, especially at high temperatures (30 °C and 32 °C) compared to low temperatures (18 °C and 22 °C) (Table 2). Satar et al. (2008) investigated the development time of *Aphis gossypii* (Glover) (Hemiptera: Aphididae) and *M. persicae* on pepper (bell pepper) leaves at different temperatures and found that the development time of *M. persicae* at 25 °C was 5.1 days. In this study, it was calculated as 8.27 days at 25 °C. This difference is thought to be due to host preference. Davis et al. (2006) calculated the growth threshold temperature, optimum temperature, and maximum temperature as 6.5 °C, 26.7 °C, and 37.3 °C, respectively, using linear and non-linear (Logan and Lactin) models on Chinese cabbage leaves. In this study, the growth threshold temperature, optimum temperature, and maximum temperature were found to be 3.9 °C, 27.5 °C, and 35.95 °C, respectively.

Barbosa et al. (2011) found the total longevity of *M. persicae* on Ligia pepper variety at different temperatures (15 °C, 20 °C, 25 °C, 30 °C) as 45 days at 15 °C, 39 days at 20 °C, 27 days at 25 °C and 24 days at 30°C, respectively. As in all insects, the longevity of *M. persicae* is shortened when the temperature rises above a certain threshold, especially as respiratory activity is negatively affected (Baral et al. 2022). As seen in these similar studies, the lifespan of *M. persicae* decreases as temperature increases. It is observed that the temperature factor affects all survival activities of the insect, especially during the pre-adult stages; they are highly affected at high temperatures and die before becoming adults. In most temperature ranges, 1–2nd nymphal mortality was higher than 3–4th nymphal mortality, whereas at 32.5 °C, high mortality was observed across all nymphal stages (Kim et al. 2004). The fact that aphids reach higher populations at low temperatures (15–29 °C), and that adult life expectancy and fecundity are high at these temperatures (Baral et al. 2022). The occurrence of winged individuals at low temperatures (18 °C and 22 °C) in the study may also be due to the excessive increase in the population. The effect of temperature on biochemical reactions and resulting arthropod activity can enhance or limit the effectiveness of integrated pest management (IPM). In integrated pest management, pests such as temperature can be managed without or with minimal environmental and economic losses, creating environments where plants are not adversely affected (Horn 2019).

CONCLUSION

In this study, using six different constant temperatures, it was found that the survival, reproduction, development, and life table parameters of *M. persicae* differed with changes in temperature.

The data from this study showed that different temperatures affect all reproductive, developmental, and life-table parameters of the pest, and that the pest is particularly negatively affected by high temperatures. It was observed that the population of the pest remained low, especially at high temperatures, and the survival rates decreased considerably at these temperatures (30 °C and 32 °C). This study will contribute to pest control by leveraging temperature factors. As shown, temperature affected all essential activities and parameters of *M. persicae*. Especially at temperatures above 30 °C, *M. persicae* may be controlled without any other control. The results of this study will contribute to pest management that does not harm plants, especially in areas such as greenhouses and seedling areas where controlled climatic conditions are provided.

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