Influence of Different Temperature Regimes on the Biological Parameters of *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae)[1]

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Abstract The red palm weevil, *Rhynchophorus ferrugineus* (Olivier), is a notorious insect pest that affects palm species worldwide. Temperature plays a significant role in regulating the colonization, population dynamics, survival, fecundity, and seasonal abundance of this pest. Therefore, the present study investigated the phenological response of *R. ferrugineus* under various temperature conditions, specifically 15, 20, 25, 30, 35, and 40°C. Observations were focused on the larval developmental period, pupal duration, adult longevity, sex ratio, and fecundity of *R. ferrugineus*. The newly emerged grubs were provided with a soft portion of sugarcane stem in plastic boxes equipped with mesh tops for ventilation under controlled laboratory conditions. Among the tested temperature regimes, 30°C was found to be the most suitable for the development, survival, and reproduction of *R. ferrugineus*. The minimum total larval developmental duration (39.48 d), maximum larval survival (44.60%), pupal formation (71.68%), adult emergence (100%), and adult weevil lifespan (123.40 d for males and 115.29 d for females) were noted at 30°C. However, the maximum fecundity (181.40) was observed at 35°C. In contrast, the longest developmental durations, minimum survival rate, and minimum reproduction were recorded at the lowest temperature (15°C). Overall, the optimum temperature for *R. ferrugineus* growth and reproduction was approximately 30°C. Lower temperatures (15°C and 20°C) and higher temperature (40°C) were found to be unsuitable, negatively affecting development, survival, and reproduction. These findings will be valuable for developing effective strategies to manage *R. ferrugineus*.

Key Words red palm weevil, date palm, biology, temperature regimes

The date palm (*Phoenix dactylifera* L.) is the most common and extensively cultivated plant in the arid and semiarid regions of North Africa, the Middle East, and South Asia (Rasool et al. 2020). It is a perennial, dicotyledonous tree belonging to the Arecaceae family and the genus *Phoenix*. This crop holds significant economic and nutritional value as it is rich in dietary fiber, vitamins, minerals, polyphenols,

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carotenoids, and phytosterols (Al-Farsi and Lee 2012, Siddiqi et al. 2020). Date palm orchards are commonly established in Iran, Saudi Arabia, Iraq, the United Arab Emirates, Egypt, Pakistan, and Algeria (Alotaibi et al. 2023).

Rhynchophorus ferrugineus Olivier (Coleoptera: Curculionidae), commonly known as the red palm weevil, is a highly destructive insect pest and is recognized as a tissue-boring pest of date palms worldwide (EPPO 2008). *Rhynchophorus ferrugineus* was originally described in India in 1891 as a regular pest of coconut and date palms (Kontodimas et al. 2017). Over time, this pest has undergone substantial adaptation, emerging as a major and highly damaging threat to date palm trees on a global scale (Aziz 2024, Dembilio et al. 2012, Montiel et al. 2022). Notably, there has been a significant increase in the prevalence of infestations since the mid-1990s, with a substantial rise occurring after 2004. Generally, the adults of *R. ferrugineus* are attracted to broken or damaged parts of palm trees, though healthy palm trees are not entirely spared (El-Shafie and Faleiro 2020). Females lay eggs in the splitting bark or wounds on the stems and leaves near the surface (Ferry and Gomez 2002). The newly emerged larvae bore into the stem and begin feeding on the surrounding tissues within the trunk, often leading to the death of the trees. Mature larvae pupate inside cocoons located at the base of the stem or beneath the soil surface. Typically, all life stages of the pest can be spotted within a palm tree (Abraham et al. 1998, Ferry and Gomez 2002). Understanding the ecological adaptations at various temperatures and the detailed life cycle of *R. ferrugineus* is very important for identifying the optimal timing to devise and implement management strategies and tactics (Peng et al. 2016).

As evident from the work of various researchers, temperature, apart from other abiotic factors, is considered the most crucial factor affecting the developmental stages of insects (Bale et al. 2002; Salama and Abdel-Razek 2002; Zhang et al. 2016, 2021). The occurrence of an insect pest during different months provides an insight into the effect of temperature on its developmental stages. This information could serve as a critical factor for forecasting and implementing control measures against the pest. Temperature has been identified as a key factor influencing insect reproduction, movement, and distribution (Andreadis et al. 2017). To date, numerous researchers in various palm-growing countries have studied larval development, adult longevity, and fecundity of *R. ferrugineus* (Faleiro et al. 2002, Murphy and Briscoe 1999, Salama et al. 2009). Abe et al. (2009) observed the effect of seasonal changes on the lifespan of weevils in southern Japan; Salama et al. (2002) studied the effect of temperature on the developmental duration and adult emergence of *R. ferrugineus* in Egypt. There is a significant gap in knowledge regarding the detailed temperature effects on the larval development, population dynamics, and fecundity of *R. ferrugineus*, except for the study by Li et al. (2010) in Wenchang, China. To address this gap, temperature-dependent experiments on *R. ferrugineus* are very important to understand its population dynamics, predict the population peaks during different months of the year, and formulate integrated management programs (Régnière et al. 2012).

On the basis of these facts, this study was conducted to investigate the effect of different temperatures on the bionomics of *R. ferrugineus*. This research is expected to help assess the population levels of *R. ferrugineus* during different periods of the year in palm-growing countries around the globe. In addition, this

study will contribute to devising effective and ecofriendly strategies and tactics to manage the population levels of this pest within tolerable limits.

Materials and Methods

Collection of insects. Immature stages of *R. ferrugineus* were collected from a stock culture maintained in a laboratory of the Department of Entomology, Gomal University, Dera Ismail Khan, Pakistan. The collected stages were transferred separately to plastic jars measuring 15 × 5 cm for multiplication under controlled conditions at temperatures of 15, 20, 25, 30, 35, and 40°C, with a 14:10-h (dark:light) photoperiod and 65% ± 5% relative humidity. The larvae and adults were reared on sugarcane sets weighing 20 mg each supplemented with 10 mg of honey solution for 1 wk. After this period, the jars were cleaned using muslin cloth washed with water and kept in sunlight for 5 min. The weevils' food was replaced every alternate day for a week. Subsequently, the stages were placed in designated jars for feeding, mating, and oviposition.

Development of larvae. Newly hatched grubs of weevils were provided with soft portions of sugarcane sets in jars measuring 12.7 × 15.24 cm. Each sugarcane set, 5 cm long and weighing 35 g, was provided to the weevil grubs to feed on under each temperature treatment. A completely randomized design was used for the life-history parameter experiments, with each treatment replicated three times (20 grubs per replicate). The larvae were observed daily for molting, and data were recorded. The duration of each larval instar was noted at all tested temperatures until pupation occurred. To prevent fungal growth, the larval food was replaced every alternate day, and the grubs were transferred to new jars. The total developmental duration for each larva at each temperature was noted.

Larval survival, pupal stage, and sex ratio. The larval survival rate in each temperature was calculated as:

$$\frac{\text{Number of larvae that successfully molted to the next instar}}{\text{Total number of larvae at the start of the instar}} \times 100$$

For pupation, date palm trunk fiber was provided to facilitate the formation of cocoons. The cocoons were carefully collected and transferred to new jars for adult emergence, and the pupal duration was noted. Sex ratio was determined as:

$$\frac{\text{Number of females emerged}}{\text{Total number of adults emerged}} \times 100$$

Adult lifespan. Newly emerged adults from each temperature were collected and transferred to rearing jars (15 × 30 × 30 cm) to record data. In total, 60 adults (30 males + 30 females) were used for each temperature, with three replicates (20 adults per replicate). After transferring the adults to new jars, the jar openings were covered with mesh gauze to prevent escape. The adults were provided with sugarcane stems to feed on, as well as for oviposition. The adults were observed daily to monitor mortality rate, and dead adults were removed from the jars. Data were recorded until 100% mortality of the weevils was achieved.

Fecundity. A total of 10 pairs of adults was used for fecundity observations at each treatment. Each pair served as a replicate for the respective treatment and was kept individually in a separate jar. The jars were carefully inspected daily to collect weevil eggs, and the number of eggs laid by each female under each temperature was recorded.

Preoviposition, oviposition and postoviposition periods. The duration from the emergence of female adults to the first egg-laying event was considered the preoviposition period. The duration between the first and last egg-laying events was recorded as the oviposition period. The duration from when females stopped laying egg until their mortality was noted as the postoviposition duration.

Statistical analysis. The biological parameters were analyzed by analysis of variance using the analytical software Statistix 8.1v (Tallahassee, FL). The means of the parameters were separated using the least significant difference test at $\alpha \leq 0.05$.

Results

Temperature effect on red palm weevil larval developmental time (days). The temperature regimes significantly affected the developmental duration of the first larval instar of *R. ferrugineus*. The maximum duration of the first instar was 11.80 d when weevils were reared at the lowest tested temperature of 15°C, which was significantly longer than the developmental durations recorded at other tested temperatures ($F = 128$, df $= 5$, $P < 0.001$). In contrast, the minimum first instar duration of 6.20 d was observed at 30°C (Table 1). Similarly, the maximum duration of the second instar was 23.73 d at 15°C, which was significantly longer than those at other tested temperatures ($F = 1779$, df $= 5$, $P < 0.001$). The minimum second instar duration of 5.60 d was observed when larvae of *R. ferrugineus* were cultured at 30°C (Table 1). The tested temperatures significantly affected the developmental duration of third instar larvae ($F = 1275$, df $= 5$, $P < 0.0001$). The maximum duration (16.80 d) of the third instar larvae was recorded at 15°C, which was statistically longer than at all other tested temperatures. In contrast, the minimum developmental duration (6.11 d) of the third instar larvae was recorded at 30°C (Table 1).

The maximum developmental duration of fourth instar larvae was 14.20 d at 15°C, which was significantly longer than at other tested temperatures ($F = 1218$, df $= 5$, $P < 0.0001$). In contrast, the minimum duration (6 d) of the fourth instar was observed at 30°C (Table 1). Similarly, the minimum developmental duration of the fifth instar larvae at 30°C was 5.40 d, which is significantly shorter than at other tested temperature regimes ($F = 944$, df $= 5$, $P < 0.0001$). The maximum duration (13.60 d) of the fifth instar was observed at 15°C (Table 1). Similarly, the maximum duration (11.10 d) of the sixth instar larvae was observed when *R. ferrugineus* was reared at 15°C, which was statistically longer than at the other tested temperature regimes ($F = 1428$, df $= 5$, $P < 0.0001$). In contrast, the minimum duration (5.10 d) of the sixth instar was recorded at 30°C (Table 1). The tested temperature regimes significantly ($F = 1627$, df $= 5$, $P < 0.0001$) affected the duration of the seventh instar larvae of *R. ferrugineus*. The minimum developmental duration of 5.00 d was recorded at 30°C, whereas the maximum duration (11.40 d) of the seventh instar larvae was observed at 15°C (Table 1).

Table 1. Effect of different temperatures on the larval durations of *Rhynchophorus ferrugineus*.

Temperature (°C)	Duration of Larval Instars (d)							Total Larval Duration
	First	Second	Third	Fourth	Fifth	Sixth	Seventh	
15	11.80 ± 0.23 a	23.73 ± 0.12 a	16.80 ± 0.06 a	14.20 ± 0.12 a	13.60 ± 0.23 a	11.10 ± 0.06 a	11.40 ± 0.06 a	102.70 ± 0.69 a
20	10.80 ± 0.23 b	20.80 ± 0.17 b	15.40 ± 0.23 b	13.20 ± 0.12 b	12.40 ± 0.06 b	9.40 ± 0.06 b	10.20 ± 0.06 b	92.20 ± 0.46 b
25	8.60 ± 0.17 c	12.40 ± 0.17 c	12.12 ± 0.14 c	10.80 ± 0.12 c	9.80 ± 0.06 c	8.20 ± 0.06 c	8.40 ± 0.06 c	70.32 ± 0.19 c
30	6.20 ± 0.12 e	5.60 ± 0.15 f	6.11 ± 0.01 f	6.00 ± 0.01 e	5.40 ± 0.06 f	5.10 ± 0.06 f	5.00 ± 0.06 f	39.48 ± 0.18 f
35	7.90 ± 0.12 d	8.40 ± 0.12 d	9.00 ± 0.06 d	8.60 ± 0.06 d	7.90 ± 0.06 d	7.20 ± 0.06 d	7.40 ± 0.06 d	56.47 ± 0.35 d
40	8.40 ± 0.17 cd	7.00 ± 0.29 e	8.40 ± 0.06 e	8.80 ± 0.06 d	6.20 ± 0.06 e	6.20 ± 0.06 e	6.80 ± 0.06 e	51.8 ± 0.52 e

In the columns, means followed by different letters are significantly different from each other at $P < 0.05$.

Total larval duration (days). The tested temperature regimes significantly affected the total larval duration of *R. ferrugineus* ($F = 3122$, df $= 5$, $P < 0.0001$). Among the tested temperatures, the lowest temperature of 15°C significantly prolonged the developmental duration. The maximum total larval duration (102.70 d) was observed at 15°C, whereas the minimum duration (39.48 d) was recorded at 30°C (Table 1).

Effect of temperature regimes on larval survival rate (%). The larval survival rate of *R. ferrugineus* at 30°C was significantly higher than at the other tested temperatures ($F = 368$, df $= 5$, $P < 0.0001$). The highest larval survival rate of 44.60% was recorded at 30°C, whereas the lowest survival rate of 17.60% was observed at 15°C (Table 2).

Effect of temperature regimes on percent pupal formation. The rearing temperatures significantly affected the percent pupal formation of *R. ferrugineus* ($F = 465$, df $= 5$, $P < 0.0001$). The maximum pupal formation of 71.68% was recorded at 30°C, whereas the minimum pupal formation of 23.07% was recorded at 40°C (Table 2).

Effect of temperature regimes on adult emergence (%). The rearing temperatures significantly affected the percent adult emergence of *R. ferrugineus* ($F = 89.90$, df $= 5$, $P < 0.0001$). The maximum adult emergence of 100% was recorded at 30°C, which was significantly different from all other tested temperature regimes. In contrast, the minimum adult emergence of 78.20% was documented at the lowest rearing temperature of 15°C (Table 2).

Effect of temperature regimes on adult lifespan (days) and female ratio. All the rearing temperatures had a significant influence on the adult longevity of male ($F = 253$, df $= 5$, $P < 0.0001$) and female *R. ferrugineus* ($F = 284$, df $= 5$, $P < 0.0001$). The maximum male longevity of 123.40 d was documented at 30°C, statistically longer than at the other temperature regimes. Similarly, the maximum female longevity of 115.29 d was recorded at 30°C, also statistically longer than at the other temperature regimes. In contrast, the shortest longevity for males and females was 98.52 d and 91.62 d, respectively, when weevils were cultured at 15°C (Table 2). Additionally, all tested temperatures had a nonsignificant effect ($F = 1.08$, df $= 5$, $P = 0.42$) on the female ratio of *R. ferrugineus* (Table 2).

Effect of temperature regimes on preoviposition, oviposition, and postoviposition durations (days). The maximum preoviposition period (6.99 d) was observed when *R. ferrugineus* females were cultured at 15°C, which was significantly different from the other treatments ($F = 10793$, df $= 5$, $P < 0.0001$). In contrast, the minimum preoviposition period (3.86 d) was recorded at 40°C. During periods of oviposition, a maximum of 85.22 oviposition days was recorded when weevils were reared at 30°C, significantly higher than at the other tested temperatures ($F = 416$, df $= 5$, $P < 0.0001$). The minimum oviposition period (69.60 days) was observed at 15°C, which was statistically lower than at all other temperature regimes. The maximum postoviposition period (24.68 d) was observed when *R. ferrugineus* females were reared at 30°C, which was statistically higher than at the remainder of the treatments ($F = 53647$, df $= 5$, $P < 0.0001$). However, the minimum postoviposition period (15.04 d) was recorded at 15°C (Fig. 1).

Effect of temperature regimes on fecundity (number of eggs/female). The rearing temperatures significantly affected the fecundity of *R. ferrugineus* females

Table 2. Effect of different temperatures on the biological parameters of *Rhynchophorus ferrugineus*.

Temperature (°C)	Larval Survival (%)	Pupal Formation	Adult Emergence (%)	Male Adult Longevity	Female Adult Longevity	Female Ratio
15	17.60 ± 0.40 f	23.61 ± 0.80 e	78.20 ± 0.62 e	98.52 ± 0.42 f	91.62 ± 0.48 f	53.72 ± 0.55 a
20	23.80 ± 0.35 e	40.75 ± 1.25 d	90.34 ± 0.82 d	115.78 ± 0.70 b	103.29 ± 0.59 c	52.76 ± 0.65 a
25	26.95 ± 0.28 d	45.70 ± 0.71 c	95.59 ± 0.84 b	111.54 ± 0.73 c	101.23 ± 0.57 d	53.06 ± 0.56 a
30	44.60 ± 0.92 a	71.68 ± 0.85 a	100.00 ± 0.87 a	123.40 ± 0.37 a	115.29 ± 0.47 a	54.37 ± 0.41 a
35	34.70 ± 0.40 b	57.01 ± 0.77 b	94.40 ± 0.86 bc	109.80 ± 0.49 d	108.58 ± 0.44 b	53.45 ± 0.62 a
40	31.80 ± 0.23 c	23.07 ± 0.78 e	92.28 ± 0.77 cd	102.81 ± 0.55 e	94.78 ± 0.54 e	52.48 ± 1.02 a

In the columns, means followed by different letters are significantly different from each other at $P < 0.05$.

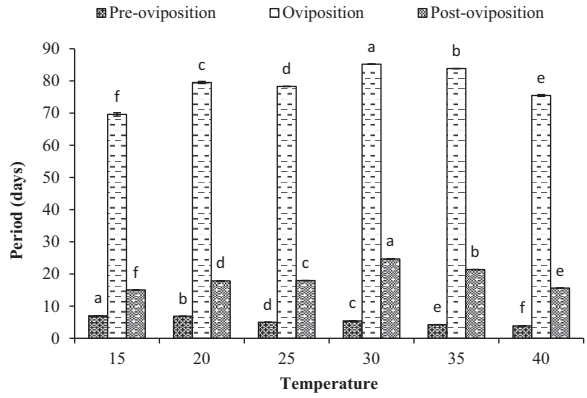

Fig. 1. Preoviposition, oviposition, and postoviposition periods of *Rhynchophorus ferrugineus* cultured at different temperatures.

($F = 3750$, df $= 5$, $P < 0.001$). Among the tested temperatures, the highest fecundity (181.40 eggs/female) was recorded when weevils were reared at 35°C, which is statistically higher than at the other tested temperatures. The lowest fecundity (46.20 eggs/female) was recorded at 15°C (Fig. 2).

Discussion

Temperature plays a significant role in regulating the colonization, population dynamics, survival, fecundity, and seasonal abundance of insect pests (Li et al. 2010). Therefore, understanding the impact of temperature on the population dynamics of insect pests is crucial for predicting possible population changes and for executing effective, economical, and ecofriendly pest control strategies, especially in the context of global warming (Kroschel et al. 2013). Several studies have examined the effect of temperature regimes on insects and found that temperature

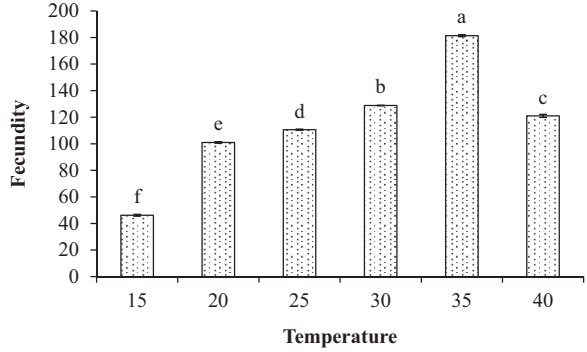

Fig. 2. Fecundity of *Rhynchophorus ferrugineus* cultured at different temperatures.

is one of the key abiotic factors that regulate development, existence, reproduction, and seasonal occurrence. It has been observed that all insects have an optimum temperature range for population growth, with significant limitations on their biology at temperatures above or below the ideal range (Li et al. 2015, Zhao and JüRui 2010, Zhou et al. 2010). According to Peng et al. (2016), *R. ferrugineus* populations persisted under temperatures ranging from 21 to 36°C, with the ideal temperature for this pest being 27°C. These findings are consistent with the significant population increase observed in China.

On the basis of our study, the developmental durations of *R. ferrugineus* were significantly affected by the tested temperatures. We observed that the lowest temperature of 15°C resulted in the maximum total larval duration, whereas the minimum total larval duration was recorded at 30°C. The development of larval stages was most rapid at 30°C compared with the other temperatures tested, suggesting that this is the most favorable temperature for *R. ferrugineus*. It was also noted that the developmental duration increased at lower temperatures of 15, 20, and 25°C. The maximum total larval duration at 15°C could be attributed to reduced metabolism at lower temperatures, as reported in various pests (Hou and Weng 2010, Li et al. 2015). Similarly, Peng et al. (2016) reported the maximum total larval duration of 215.4 d at 21°C. However, Li et al. (2010) found that *R. ferrugineus* was unable to complete its development at 16°C and 40°C, contradictory results to the present findings. In agreement with our study, shorter developmental durations were observed in *Callosobruchus chinensis* L. at 32°C (Omar and Mahmoud 2020) and *Dermestes maculatus* De Geer at 30°C (Martín-Vega et al. 2017, Zanetti et al. 2016).

In the present study, larval survival, pupal formation, adult emergence, and male and female longevity were significantly influenced by the different temperature regimes. The maximum larval survival, pupal formation, and adult emergence were observed at 30°C, indicating that this temperature is optimal for the survival and growth of *R. ferrugineus*. This is consistent with previous findings, in which the maximum population growth of *R. ferrugineus* was noted at its optimum temperature (Peng et al. 2016), as well as in other insects such as *C. chinensis* L., *Heliothis viriplaca* (Hufnagel), *Dermestes frischii* Kugelan, *D. maculatus*, and *Dermestes undulatus* Brahm (Cui et al. 2018, Martín-Vega et al. 2017, Omar and Mahmoud 2020). The maximum male and female longevities were found at 30°C and minimum at lower and higher temperatures. This trend of adult longevity has been reported for *R. ferrugineus* by others (Peng et al. 2016, Zhao and JüRui 2010).

The rearing temperatures also had marked effects on the fecundity of *R. ferrugineus* females, with maximum fecundity recorded at 35°C. The minimum fecundity was recorded at the lowest temperature of 15°C, indicating that this temperature is unsuitable for the reproduction of *R. ferrugineus*. The present study demonstrated that intermediate temperatures (30°C and 35°C) were most suitable for the fecundity of *R. ferrugineus* and played an important role in increasing its population. In agreement with these results, it has previously been reported that *R. ferrugineus* females laid the maximum number of eggs at 28°C to 32°C (Li et al. 2010) and 27°C (Peng et al. 2016). Similarly, maximum fecundity was observed in *Gastrophysa viridula* (De Geer) at 18°C, *Bradysia odoriphaga* Yang & Zhang at

25°C (Li et al. 2015), *Spodoptera frugiperda* (J. E. Smith) at 30°C (Chen et al. 2022), and *H. viriplaca* at 31°C (Cui et al. 2018).

The present study examined the biological parameters of *R. ferrugineus* at various temperatures ranging from 15 to 35°C to predict their population dynamics. Temperatures between 30 and 35°C were found to be the most suitable for the growth and reproduction of *R. ferrugineus*. Additionally, apart from temperature, various biotic and abiotic factors may influence insect population dynamics, for instance host plants (Dogar et al. 2018), nutrients (Tuan et al. 2014), and insecticide applications (Yu et al. 2012). It is worth noting that the population dynamics of *R. ferrugineus* may differ when observed under laboratory conditions compared with its proliferation under field conditions. Therefore, it is important to explore more under natural conditions to gain deeper insights into the population dynamics of *R. ferrugineus*.

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