



## Life table and predation capacity of predatory mite *Neoseiulus californicus* (Acari: Phytoseiidae) feeding on *Tetranychus urticae* Koch (Acari: Tetranychidae) and some plant pollens

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### Abstract

The supply of pollens as an alternative food can enhance the performance of phytoseiid predatory mites. The effects of three different pollens (sunflower, tamarix, and common mallow) as supplementary diets on the life table and predation rate of *Neoseiulus californicus* McGregor (Acari: Phytoseiidae) in the absence or presence of *Tetranychus urticae* Koch (Acari: Tetranychidae) were determined. The chemical compositions of pollens were determined too. The results showed that the fecundity of *N. californicus* on *T. urticae* in the presence of pollen was significantly higher than that on pollen alone. The intrinsic rate of increase on *T. urticae* in the presence of tamarix and common mallow pollens ( $0.131$  and  $0.132 \text{ day}^{-1}$ ) was significantly higher than those on the other diets. The net reproductive rate varied from  $0.080$  (on sunflower pollen) to  $8.60$  offspring (on tamarix pollen+ *T. urticae*). The cohort reared on common mallow pollen + *T. urticae* diet had the highest intrinsic rate of increase as well as the finite rate of increase, followed by tamarix pollen + *T. urticae*. The predation rate of *T. urticae* by *N. californicus* fed on tamarix pollen was the highest value compared to other pollens. The protein content was higher in tamarix pollen, while the content of lipid, phenol, and flavonoid was greater in sunflower pollen. Due to its higher protein content, tamarix pollen had favorable effects on the survival, development, fecundity, and predation rate of *N. californicus*. Therefore, *N. californicus* reared on tamarix pollen can be useful for controlling *T. urticae*.

**Keywords:** Biological control; Fecundity; Intrinsic rate of increase; Predation rate; Survival rate



## Introduction

With the raising world population, increasing the quantity and quality of crops to provide food resources and food security is one of the agricultural sector's important goals. One of the problems in achieving this goal is the existence of agricultural pests that cause significant damage to crops every year. Therefore, reducing the abundance of pest populations is essential to maintain the quantity and quality of agricultural products (Rodrigues et al., ۲۰۲۳). Two-spotted spider mite, *Tetranychus urticae* Koch (Acari: Tetranychidae), is a herbivorous pest that has become a serious problem in greenhouse and field crops such as cucumber, beans, and soybeans because the excessive use of chemical acaricides has eliminated many of their natural enemies. On the other hand, the high reproduction rate and short generation length have quickly made the two-spotted spider mite resistant to various acaricides (Khanamani et al., ۲۰۱۷a).

One common method of reducing damage from pests, such as the two-spotted spider mite, in various countries, especially developing countries like Iran, is the use of chemical pesticides (Havasi et al., ۲۰۲۰). However, the continuous and incorrect use of acaricides has led to the emergence of mites resistant to them and the elimination of non-target natural enemies. Also, there is concern about the side effects of their residues on plant products, environmental pollution, and threats to human health (Fathipour and Maleknia, ۲۰۱۶; Rodrigues et al., ۲۰۲۳). Therefore, the use of environmentally friendly mite pest management programs, such as biological control is expanding due to the importance of crop production and economic losses from mites, as well as the problems caused by applying chemical acaricides and the ban on their use (Fathipour and Maleknia, ۲۰۱۶; Havasi et al., ۲۰۲۰). Biological control using parasitoids, pathogens, predators, antagonists, or competing microorganisms is a suitable alternative to chemical control. In addition to decreasing pest populations, reducing pest resistance to pesticides, and preserving natural resources and human health, this method can increase the quantity and quality of crops and the sustainable development of the agricultural sector (Hajek and Eilenberg, ۲۰۱۸).

Predatory mites can be used as biological control agents to manage pests, especially mites (Fathipour and Maleknia, ۲۰۱۶). Among them, phytoseiid mites are generalist predators that can feed on various plant mites, thrips, whiteflies, plant pollen, fungi, and nematodes (Khanamani et al., ۲۰۱۷a; Eini et al., ۲۰۲۲). The type of diet used in rearing these predatory mites is very important. Pollen grains can be used as an available food source for the mass rearing phytoseiid mites. Using them is significantly important when the population of natural prey (e.g., two-spotted spider mites) is low and leads to reduced rearing costs (McMurtry et al. ۲۰۱۳). In addition to increasing the efficiency of mass-rearing predatory mites, identifying and using available plant pollens with high nutritional value can improve their efficiency as biological control agents and reduce prey populations (Hashemi et al., ۲۰۲۱). Pollen offers a significant source of nutrients essential for phytoseiid mites; however, the nutritional value of pollen from various plants varies, resulting in differing impacts on the life stages of predatory mites (Khanamani et al., ۲۰۱۷c; Pascua et al., ۲۰۲۰). Some phytoseiid species gain higher reproductive ability by feeding on plant pollens, and the survival and viability of their embryonic stages increase (Khanamani et al., ۲۰۱۷b; Soltaniyan et al., ۲۰۱۸).

Predatory mite *Neoseiulus californicus* (McGregor) is an important species of the Phytoseiidae family and is native to the Mediterranean region. This species feeds on spider mites from the Tetranychidae and Tarsonemidae families and successfully controls mite populations in fields and greenhouses (Havasi et al., ۲۰۲۰). This predatory mite is one of the natural enemies of the two-spotted spider mite, which is suitable for biological control of this pest in various climatic conditions (Khanamani et al., ۲۰۱۷a). In addition to two-spotted spider mites, this predator is capable of feeding on other small pests, such as thrips and plant pollens. Therefore, in times of scarcity of its main prey, it can survive and reproduce by feeding on other alternative food sources, such as plant pollens (Gugole Ottaviano et al., ۲۰۱۵). The possibility of mass rearing this predatory mite on a pollen-containing diet has increased interest in using this predator as a biological control agent (Khanamani et al., ۲۰۱۷a).

For mass rearing of predatory mites, examining life table parameters is a useful tool for determining survival, developmental duration, and reproduction. This table identifies the most vulnerable age and developmental stage with high mortality rates and predicts population growth (Carey, ۱۹۹۳). Numerous experiments have been conducted on the biological parameters of the predatory mite *N. californicus* reared on various diets (Khanamani et al., ۲۰۱۷c; Eini et al., ۲۰۲۲). Researchers reported that *N. californicus* shows the highest total fecundity when feeding on pistachio pollen (Soltaniyan et al., ۲۰۱۸). Predatory mite *N. californicus* is reported to have the longest adult longevity by feeding on almond pollen (Khanamani et al. ۲۰۱۷b). Laboratory studies can provide valuable information for mass production programs of pollen-feeding natural enemies and biological pest control projects. Therefore, this study investigated the life table parameters and the predation rate of *N. californicus* rearing on common mallow, tamarix, and sunflower pollens,

alone and in the presence of two-spotted spider mite nymphs and evaluated the best pollen for feeding predatory mites. Also, the compositions of common mallow, tamarix, and sunflower pollens were studied.

## Materials and Methods

### Host plant cultivation

The seeds of bean (*Phaseolus vulgaris* L., cv. Khomein), as a host plant, were soaked in plastic containers for three days to germinate. Then, five-six germinated seeds were transferred to the plastic pots (diameter 10 cm and height 12 cm) containing perlite and peat moss (1:1 ratio). The plants were kept in a room with a photoperiod of 16:8 h (light:darkness) and temperature of 20 °C. The pots were irrigated daily as needed and before the soil was completely dry. Every day, plants infected with pests and diseases were removed from the keeping place.

### Rearing of two-spotted spider mite

The two-spotted spider mite was collected from infected bean plants in the University of Zabol's research greenhouse. The mites were reared in the laboratory on detached bean leaves placed on wet cotton wool in plastic containers. The containers were maintained in a growth chamber at  $20 \pm 2$  °C with a 16:8 (light: darkness) photoperiod, and  $60 \pm 5\%$  relative humidity. Fresh bean leaves were provided three times a week to ensure a continuous and stable supply of healthy mites for experimental purposes. After rearing three generations, the resulting colony was used for the experiment.

### Rearing of predatory mite

The predatory mite *N. californicus* was purchased from the Koppert (the Netherlands). To rear this mite, the required conditions were a relative humidity of  $60 \pm 5\%$ , temperature of  $20 \pm 1$  °C, and photoperiod of 16:8 h (light:darkness). A plastic plate (talc) placed on a water-saturated sponge inside a plastic container filled with water was used to rear this predatory mite. To prevent mites from escaping, strips of wet paper towels were placed on the edges of these plastic plates. Two-spotted spider mite as bait along with a mixture of pollens used in this research was poured on the rearing substrate (bean leaf) using a fine brush every three days. The adult predatory mites were transferred from the primary colony on this substrate using a wet fine brush. Predatory mites were reared on bean leaves infested with two-spotted spider mites. Different biological stages of two-spotted spider mites and tested plant pollens were used to rear this predatory mite (Hatherly et al., 2005).

### Preparing plant pollens

In this research, common mallow (*Malva sylvestris* L.), tamarix (*Tamarix aphylla* L.), and sunflower (*Helianthus annuus* L.) pollens were collected from their natural habitats in Sistan and Baluchestan Province, Iran, on a sunny day. Common mallow and sunflower pollens were gathered from flowering plants growing in rangelands and agricultural margins. Tamarix pollen was collected from mature trees in arid regions near Zabol. Then, the cleaned pollen was oven-dried at 30 °C for 48 hours to reduce moisture content and prevent microbial contamination. For long-term storage, the pollen was frozen at -20 °C. For short-term use, pollen was stored in airtight containers at 4 °C for up to 2 weeks during the experiments.

### Experimental unit

Leaf discs were prepared following the methods described by Kostianen and Hoy (1994). Freshly excised bean (variety Khomein) leaf discs, cut into sections of  $1.0 \times 1.0$  cm, were placed upside down in Petri dishes (7 cm in diameter) on a cotton layer saturated with water, in which a 6-mm-diameter hole was drilled. This also prevented the mites from leaving the arenas and drowning. Cotton threads were arranged in circular barriers with a thickness of 0.5 cm to prevent predators from escaping and maintain humidity. The prepared Petri dishes were placed inside larger dishes with a diameter of 10 cm. Water was added daily to the larger dishes to keep the leaves fresh. The mixture of pollen and eggs was replaced daily during both the immature development and adult stages of mites. All petri dishes were kept at  $20 \pm 1$  °C,  $70 \pm 5\%$  relative humidity, and photoperiod of 16:8 h (light: darkness) in a growth chamber.

### Life history study

In this study, 0.5 mg of pollen from the tested plant species and 20 eggs of *T. urticae* were provided daily to the larvae and nymphs in each Petri dish. A total of six treatments were evaluated, which included pollen from common mallow, eucalyptus, tamarisk, and sunflower, as well as combinations of these pollen sources with kindly bean leaves containing *T. urticae* eggs. The control group consisted of kindly bean leaves supplemented solely with *T. urticae* eggs. For treatments involving natural prey, 20 eggs of the two-spotted spider mite (*T. urticae*) along with leaf discs were added to the experimental arenas daily. To minimize fungal contamination, the leaf discs inside the Petri dishes were replaced every 24 h. Food availability and moisture levels were carefully monitored and adjusted as needed. The egg incubation period was recorded by measuring the time from oviposition to hatching. Egg mortality rates were calculated by assessing the proportion of unhatched eggs relative to the total number of eggs. Petri dishes containing predatory mites were inspected at 24-hour intervals to determine mortality rates during the larval and pupal stages, based on the number of dead larvae



and nymphs observed. The developmental duration of both the larval and pupal stages was recorded daily. Once the mites matured, the numbers of males and females were counted to establish the sex ratio in each treatment. Male mites were subsequently introduced into Petri dishes containing adult females for further observations. Daily oviposition rates were recorded and monitored until all individuals had died. Additionally, the lifespan of adult mites, along with pre-oviposition and post-oviposition periods, was documented for each treatment group.

#### Predation rate study

To prepare prey eggs for the predation rate experiment, the adult females of two-spotted spider mite were placed in each experimental unit to lay eggs, daily. The same types of experimental arenas were used for the predation rate study. After each day, females were removed without removing their web, and eggs were reduced to the needed density. To specify the prey consumption by *N. californicus*, 20 eggs of *T. urticae* were added daily to discs. Experimental units were monitored daily, the number of consumed prey individuals was recorded and the same number of new prey was added to each experimental unit. After adult emergence and pairing males and females, each pair was given 20 eggs of *T. urticae*, and the number of consumed eggs was recorded until the predators died. To separate the predation rate of males from that of females, the consumption prey rate of 20 single males was determined under similar conditions. To specify the daily consumption rate of females, the average male consumption was subtracted from the consumption of pairs (Farhadi et al., 2011; Moghadasi et al., 2014).

#### Determination of pollen chemical compositions

The chemical compositions (total carbohydrate, total lipid, and total protein) of pollens were determined as follows:

For protein extraction, pollen samples were homogenized in 50 mM potassium phosphate buffer (pH 7.2). The homogenate was centrifuged at 14,000 × g for 3 min at 4 °C. The supernatant (20 µl) was collected for protein assay and Bradford solution (200 µl) was added to it. Then, the mixture absorbance was read at 595 nm by a spectrophotometer (Elisa Microplate Reader, BioTek 800TS) according to the method described by Bradford (1976). Finally, the total protein content was reported as mg g<sup>-1</sup> using an equation obtained from the bovine serum albumin calibration curve. Total lipid content in the studied pollens was extracted by Soxhlet method using the solvent n-hexane, and the extract weight was determined by gravimetric analysis as crude lipid (Khanamani et al., 2013).

To measure the sugar content of various pollens, high-performance liquid chromatography (HPLC) (Waters, Milford, MA) equipped with a supelcogel carbohydrate column of 300 by 7.8 mm (Supelco, Bellefonte, PA) was used, as shown by Qian et al (2008). The mobile phase used was HPLC-grade water at a flow rate of 0.8 ml min<sup>-1</sup>. Before running samples, sugar standard solutions (0–1000 ppm for sucrose, glucose, and fructose) were injected into HPLC. Sugars were identified according to the retention time of standards and the peaks appearing at each retention time in injected samples. Total flavonoid content was measured by a colorimetric method at 510 nm, described by Bonvehi et al. (2001). The total phenolic content was measured using a Folin-Ciocalteu method (Bonvehi et al., 2001).

#### Statistical analysis

Before analysis, the normality of all data was tested with Mintab software. The biological parameters of predatory mites were calculated based on the age-stage, two-sex life table theory, which considers both sexes (male and female) and variable development between individuals and sex (Chi and Liu, 1985; Chi, 1988). Population parameters including the intrinsic rate of increase (*r*), finite rate of increase (*λ*), net reproductive rate (*R*0), and mean generation time (*T*) were calculated according to the Goodman (1982) method. Age-stage specific survival rate (*s<sub>xj</sub>*) (where *x* is age and *j* is stage), age specific survival rate (*l<sub>x</sub>*), age-stage specific fecundity (*f<sub>xj</sub>*), age-specific fecundity (*m<sub>x</sub>*), and population parameters were estimated using TWO SEX-MS Chart software as below:

$$l_x = \sum_{j=1}^{\beta} Sxj$$

$$m_x = \frac{\sum_{j=1}^{\beta} Sxj f_{xj}}{\sum_{j=1}^{\beta} Sxj}$$

Where, *β* is the number of stages.

Intrinsic rate of increase (*r*) was estimated using the iterative bisection method and Euler-Lotka Equation (*x* started from 0) as below (Goodman, 1982):

$$\sum_{x=0}^{\infty} e^{-r(x+1)} l_x m_x = 1$$

$$\lambda = e^r$$

$$R_0 = \sum_{x=0}^{\infty} l_x m_x$$

$$T = \frac{\ln(R_0)}{r}$$

Variance and standard error for life table statistics and population growth parameters were estimated by the bootstrap method and compared using the paired bootstrap test based on confidence interval (95%) with a sample size of 10000 (Huang and Chi, 2013). The graphs were depicted using SigmaPlot software (Sigmaplot, 2011).

Raw data of daily predation for all individuals were analyzed to calculate the predation rate according to Chi and Yang (2003) by CONSUME-MSChart software (Chi, 2014). The age-specific predation rate ( $k_x$ , the average number of consumed prey per predator of age  $x$ ) could be determined by the following formula (Chi and Yang, 2003):

$$k_x = \frac{\sum_{j=1}^{\beta} S_{xj} c_{xj}}{\sum_{j=1}^{\beta} S_{xj}}$$

Where,  $\beta$  is the number of stages and  $c_{xj}$  is the age-stage specific consumption rate of individuals at age  $x$  and stage  $j$ .

The age-specific net predation rate ( $q_x$ , the weighted number of consumed prey by a predator of age  $x$ ) showed the survival rate and was calculated as below (Chi and Yang, 2003):

$$q_x = l_x k_x$$

The net predation rate ( $C_0$ ) indicates the average number of preys consumed by a predator during its life span that was estimated as below:

$$C_0 = \sum_{x=0}^{\infty} l_x k_x = \sum_{x=0}^{\infty} q_x$$

The ratio of the net predation rate to the net reproductive rate gives the transformation rate from prey population to predator offspring, which was defined as  $Q_p$  and calculated as below Chi and Yang (2003):

$$Q_p = \frac{C_0}{R_0}$$

This rate indicates the average number of prey required for a predator to produce an egg. Standard errors of predation parameters were also calculated by the Bootstrap method.

In this research, one-way analysis of variance was performed using SPSS version 16 statistical software. Statistical differences between means were estimated based on the Tukey test ( $\alpha=5\%$ ).

## Results

### Life history

The average period of different life stages for *N. californicus* feeding on the studied pollens and also feeding on the two-spotted spider mite along with pollens was shown in Table 1. The results indicated that the longest egg period (3.9 day) and the shortest larval period (1.92 day) in *N. californicus* were obtained by feeding on sunflower pollen+ *T. urticae*, which did not differ significantly from feeding on common mallow pollen+ *T. urticae*. When exclusively feeding on each of the studied pollens, the shortest egg period and the longest larval period were observed. The longest larval period of *N. californicus* (2.62 day) was related with exclusive feeding on tamarix pollen (Table 1).

Among the six studied treatments, the tamarix + *T. urticae* treatment showed the longest protonymph period (2.57 day), which was not statistically significantly different from the tamarix pollen treatment (2.50 day). The longest deutonymph period (2.9 day) was achieved by feeding on tamarix pollen+ *T. urticae*. The shortest deutonymph period (1.59 day) was related to feeding on sunflower pollen+ *T. urticae*, which did not show a significant difference with the common mallow pollen+ *T. urticae* treatment (Table 1). Exclusive feeding on tamarix pollen resulted in the highest male longevity (17.5 day), which was not significantly different from the feeding on tamarix+ *T. urticae* (17.4 day). The longest female longevity and total life span in the predatory mite *N. californicus* were related to feeding on tamarix pollen+ *T. urticae* (19.29 day and 17.08 day, respectively) and their shortest periods (13.14 day and 7.16 day, respectively) were achieved through exclusive feeding on sunflower pollen (Table 1).

The highest preoviposition period of the female (2.80 day) was obtained with exclusive feeding on tamarix pollen and the lowest was related to the feeding on sunflower + *T. urticae* (0.14 day). The highest total preoviposition period of the



female counted from birth (۱۳,۶۸ day) was related to feeding on tamarix pollen + *T. urticae* and the lowest (۸,۶۴ day) was obtained in the treatment feeding on sunflower pollen+ *T. urticae* (Table ۱). The longest preoviposition period (۱۰,۳۸ day) was observed with feeding on tamarix pollen+ *T. urticae*, and the shortest period (۸,۵۹ day) was associated with feeding on sunflower pollen+ *T. urticae*. Among the six studied treatments, the sunflower pollen+ *T. urticae* treatment showed the highest fecundity (۱۵,۱۴ eggs/female) and the lowest value (۵,۲۶ eggs/female) was related to the exclusive feeding on common mallow pollen (Table ۱).

**Table ۱- Life history statistics (Mean  $\pm$  SE) of *Neoseiulus californicus* fed on different plant pollens and *Tetranychus urticae* eggs.**

Parameter	Sunflower	Tamarix	Common mallow	Sunflower + <i>T. urticae</i>	Tamarix + <i>T. urticae</i>	Common mallow + <i>T. urticae</i>
Egg (day)	۱,۶۷ $\pm$ ۰,۰۷ <sup>c</sup>	۱,۵۲ $\pm$ ۰,۰۷ <sup>c</sup>	۱,۵۹ $\pm$ ۰,۰۸ <sup>c</sup>	۳,۷ $\pm$ ۰,۰۷ <sup>a</sup>	۲,۵۸ $\pm$ ۰,۰۷ <sup>b</sup>	۳,۳۶ $\pm$ ۰,۰۸ <sup>a</sup>
Larva (day)	۲,۵۵ $\pm$ ۰,۰۹ <sup>a</sup>	۲,۶۲ $\pm$ ۰,۰۷ <sup>a</sup>	۲,۵۵ $\pm$ ۰,۰۷ <sup>a</sup>	۱,۹۲ $\pm$ ۰,۰۹ <sup>c</sup>	۲,۳۵ $\pm$ ۰,۰۹ <sup>b</sup>	۱,۹۶ $\pm$ ۰,۰۹ <sup>c</sup>
Protonymph (day)	۲,۴۲ $\pm$ ۰,۱۱ <sup>ab</sup>	۲,۵۵ $\pm$ ۰,۰۸ <sup>a</sup>	۲,۴۷ $\pm$ ۰,۰۳ <sup>ab</sup>	۲,۱۱ $\pm$ ۰,۰۳ <sup>c</sup>	۲,۵۷ $\pm$ ۰,۱۱ <sup>a</sup>	۱,۷۲ $\pm$ ۰,۱۵ <sup>d</sup>
Deutonymph (day)	۲,۴۴ $\pm$ ۰,۱۸ <sup>c</sup>	۲,۷۶ $\pm$ ۰,۰۸ <sup>b</sup>	۲,۶۲ $\pm$ ۰,۰۳ <sup>ab</sup>	۱,۵۹ $\pm$ ۰,۱۵ <sup>d</sup>	۲,۹۵ $\pm$ ۰,۱۹ <sup>a</sup>	۱,۷۴ $\pm$ ۰,۱۷ <sup>d</sup>
Male longevity (day)	۱۳ $\pm$ ۱ <sup>c</sup>	۱۷,۵ $\pm$ ۰,۵ <sup>a</sup>	۱۴,۷ $\pm$ ۱,۷ <sup>ab</sup>	۱۵,۶۷ $\pm$ ۰,۸۸ <sup>ab</sup>	۱۷,۴ $\pm$ ۱,۵ <sup>a</sup>	۱۵ $\pm$ ۱ <sup>b</sup>
Female longevity (day)	۱۳,۱۴ $\pm$ ۰,۶۳ <sup>d</sup>	۱۶,۷۷ $\pm$ ۱,۳ <sup>ab</sup>	۱۵ $\pm$ ۱ <sup>c</sup>	۱۷,۸۶ $\pm$ ۱,۰۲ <sup>b</sup>	۱۹,۲۹ $\pm$ ۰,۴۴ <sup>a</sup>	۱۵,۶۶ $\pm$ ۰,۴۳ <sup>c</sup>
Total life span (day)	۷,۱۶ $\pm$ ۰,۴۸ <sup>c</sup>	۱۳,۸۶ $\pm$ ۰,۶۲ <sup>b</sup>	۱۱,۱۴ $\pm$ ۰,۶۴ <sup>d</sup>	۱۱,۲۲ $\pm$ ۰,۷۳ <sup>d</sup>	۱۷,۰۸ $\pm$ ۰,۶۶ <sup>a</sup>	۱۴,۰۸ $\pm$ ۰,۵۱ <sup>c</sup>
APOP (day)	۲ $\pm$ ۰,۲۶ <sup>c</sup>	۲,۸۰ $\pm$ ۰,۰۹ <sup>a</sup>	۲,۵۲ $\pm$ ۰,۰۲ <sup>b</sup>	۰,۱۴ $\pm$ ۰,۱۴ <sup>d</sup>	۱,۲۵ $\pm$ ۰,۱۲ <sup>d</sup>	۱,۴۱ $\pm$ ۰,۱۳ <sup>d</sup>
TPOP (day)	۱۱,۱۶ $\pm$ ۰,۳۱ <sup>c</sup>	۱۲,۰۷ $\pm$ ۰,۱۴ <sup>b</sup>	۱۱,۱۴ $\pm$ ۰,۸۹ <sup>c</sup>	۸,۶۴ $\pm$ ۰,۸۶ <sup>d</sup>	۱۳,۶۸ $\pm$ ۰,۳۲ <sup>a</sup>	۱۰,۸۸ $\pm$ ۰,۳۳ <sup>c</sup>
Preoviposition day	۹ $\pm$ ۰,۵ <sup>b</sup>	۹,۲۷ $\pm$ ۰,۱۲ <sup>b</sup>	۹,۳۱ $\pm$ ۰,۱۵ <sup>b</sup>	۸,۵۹ $\pm$ ۰,۲۱ <sup>c</sup>	۱۰,۳۸ $\pm$ ۰,۲۵ <sup>a</sup>	۸,۶۳ $\pm$ ۰,۲۵ <sup>c</sup>
Fecundity (eggs/female)	۷ $\pm$ ۱,۰۱ <sup>d</sup>	۸,۵۲ $\pm$ ۰,۵۵ <sup>d</sup>	۵,۲۶ $\pm$ ۰,۴۳ <sup>d</sup>	۱۵,۱۴ $\pm$ ۱,۷۴ <sup>a</sup>	۱۲,۰۹ $\pm$ ۰,۸۸ <sup>b</sup>	۸,۱۱ $\pm$ ۰,۵۷ <sup>c</sup>

Means within a row with the same letter were not significantly different based on the Tukey test ( $\alpha = 0\%$ ).

APOP (Preoviposition period of female); TPOP (Total preoviposition period of female counted from birth)

### Population parameters

The investigation of population parameters in *N. californicus* (Table ۲) showed that the highest values in intrinsic rate of increase (۰,۱۳۲ day<sup>-1</sup>) and finite rate of increase (۰,۱۴۲ day<sup>-1</sup>) were obtained by feeding on common mallow pollen+ *T. urticae*, which did not differ significantly from feeding on tamarix pollen+ *T. urticae* (۰,۱۳۱ day<sup>-1</sup> and ۰,۱۳۱ day<sup>-1</sup>, respectively). The lowest values in intrinsic rate of increase and finite rate of increase (۰,۰۴۱ day<sup>-1</sup> and ۰,۰۹۵ day<sup>-1</sup>, respectively) were associated with exclusive feeding on sunflower pollen (Table ۲).

The highest net reproductive rate (۸,۴۶۵) of *N. californicus* was obtained by feeding on tamarix pollen+ *T. urticae*, and the lowest value (۰,۵۸۵) was related to exclusive feeding on sunflower pollen. Exclusive feeding on tamarix pollen and the treatment of common mallow pollen+ *T. urticae* did not show significant differences in net reproductive rate (Table ۲). The results of mean generation time among the six studied treatments indicated that the average period of one generation when fed with tamarix pollen+ *T. urticae* was longer (۱۶,۳۴۸ day) than other tested treatments. The lowest mean generation time (۱۲,۳۸۲ day) was obtained by feeding on sunflower pollen+ *T. urticae*. Other treatments showed no significant differences in mean generation time compared to one another (Table ۲).

**Table ۲- Population growth parameters (Mean  $\pm$  SE) of *Neoseiulus californicus* fed on different plant pollens and *Tetranychus urticae* eggs**

Life table parameters	Sunflower	Tamarix	Common mallow	Sunflower + <i>T. urticae</i>	Tamarix + <i>T. urticae</i>	Common mallow + <i>T. urticae</i>
$r$ (day <sup>-1</sup> )	۰,۰۴۱ $\pm$ ۰,۰۳۹ <sup>d</sup>	۰,۱۱۲ $\pm$ ۰,۰۰۹ <sup>b</sup>	۰,۰۷۵ $\pm$ ۰,۰۱۱ <sup>c</sup>	۰,۱۱۷ $\pm$ ۰,۰۲۰ <sup>b</sup>	۰,۱۳۱ $\pm$ ۰,۰۰۸ <sup>a</sup>	۰,۱۳۲ $\pm$ ۰,۰۰۹ <sup>a</sup>
$\lambda$ (day <sup>-1</sup> )	۰,۰۹۵ $\pm$ ۰,۰۳۶ <sup>d</sup>	۱,۱۱۹ $\pm$ ۰,۰۰۹ <sup>b</sup>	۱,۰۷۸ $\pm$ ۰,۰۱۲ <sup>c</sup>	۱,۱۲۳ $\pm$ ۰,۰۲۰ <sup>b</sup>	۱,۱۳۱ $\pm$ ۰,۰۰۹ <sup>a</sup>	۱,۱۴۲ $\pm$ ۰,۰۱۰ <sup>a</sup>
$R0$ (offspring/individual)	۰,۵۸۵ $\pm$ ۰,۲۴۲ <sup>c</sup>	۵,۲۸۶ $\pm$ ۰,۶۷ <sup>ab</sup>	۲,۸۴۵ $\pm$ ۰,۴۳ <sup>d</sup>	۴,۲۴۰ $\pm$ ۱,۰۷ <sup>c</sup>	۸,۴۶۵ $\pm$ ۰,۹۹ <sup>a</sup>	۵,۶۸۵ $\pm$ ۰,۶۵ <sup>ab</sup>
$T$ (day)	۱۳,۰۱ $\pm$ ۱,۴۴ <sup>b</sup>	۱۴,۸۰ $\pm$ ۰,۱۴ <sup>b</sup>	۱۳,۸۶ $\pm$ ۰,۱۶ <sup>b</sup>	۱۲,۳۸ $\pm$ ۰,۳۴ <sup>c</sup>	۱۶,۳۴ $\pm$ ۰,۳۳ <sup>a</sup>	۱۳,۱۱ $\pm$ ۰,۳۰ <sup>ab</sup>

Means within a row with the same letter were not significantly different based on the Tukey test ( $\alpha = 0\%$ ).

$r$  (Intrinsic rate of increase);  $\lambda$  (Finite rate of increase);  $R0$  (Net reproductive rate);  $T$  (Mean generation time)

### Predation parameters

Predation parameters of *N. californicus* fed on different plant pollens was presented in Table ۳. The net predation rate showed that the mean number of consumed prey (*T. urticae*) by the average individual *N. californicus* fed on common mallow, tamarix, and sunflower pollens during its life span was ۵۷,۸۰۴, ۸۱,۶۰۵, and ۲۶,۵۲۵ prey, respectively ( $P = ۰,۹۵$ ). The finite predation rate of *N. californicus* was also affected by pollen diets and the highest amount (۳,۲۱۵ day<sup>-1</sup>) was related to the diet of tamarix pollen (Table ۳). The transformation rate of *N. californicus* fed on common mallow, tamarix, and sunflower pollens was ۱۰,۲۷, ۹,۷۲۷, and ۶,۲۴ preys, respectively. These values showed that *N. californicus* fed on common mallow, tamarix, and sunflower pollens required ۱۰,۲۷, ۹,۷۲۷, and ۶,۲۴ *T. urticae*, respectively, to produce each egg, which the lowest value was related to the diet of sunflower pollen (Table ۳). The stable predation rate of *N. californicus* had the highest value (۲,۸۲۱ Prey/ predator) on diet of tamarix pollen, which had no significant difference with diet of common mallow pollen (Table ۳).

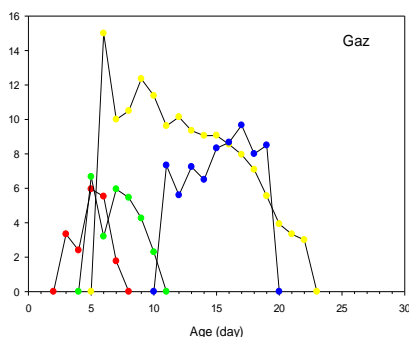
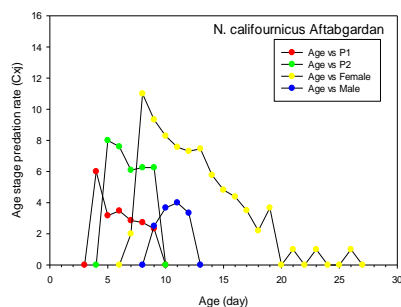
**Table ۳- Predation rates (mean±SE) of *Neoseiulus californicus* fed on different plant pollens.**

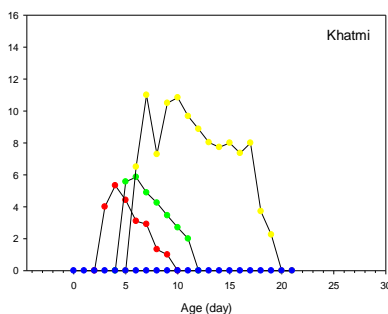
Parameters	sunflower	Tamarix	Common mallow
C (Prey)	۲۶,۵۲۵±۵,۲۲۰ <sup>c</sup>	۸۱,۶۰۵±۶,۸۰۹ <sup>a</sup>	۵۷,۸۰۴±۴,۸۳۷ <sup>b</sup>
ω (day <sup>-1</sup> )	۱,۶۰۵±۰,۲۷۲ <sup>c</sup>	۳,۲۱۵±۰,۲۰۱ <sup>a</sup>	۲,۷۶۶±۰,۲۰۵ <sup>b</sup>
Q <sub>p</sub> (Prey/ offspring)	۶,۲۴۰±۱,۰۲۷ <sup>b</sup>	۹,۷۲۷±۰,۹۰۱ <sup>a</sup>	۱۰,۲۷۰±۰,۷۲۵ <sup>a</sup>
Ψ (Prey/ predator)	۱,۴۲۹±۰,۲۲۰ <sup>b</sup>	۲,۸۲۱±۰,۱۶۳ <sup>a</sup>	۲,۴۲۳±۰,۱۶۱ <sup>a</sup>

Means within a row with the same letter were not significantly different based on the Tukey test ( $\alpha = ۵\%$ ).

C (Net predation rate); ω (Finite predation rate); Q<sub>p</sub> (Transformation rate); Ψ (Stable predation rate).

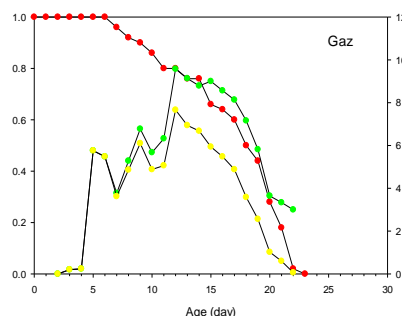
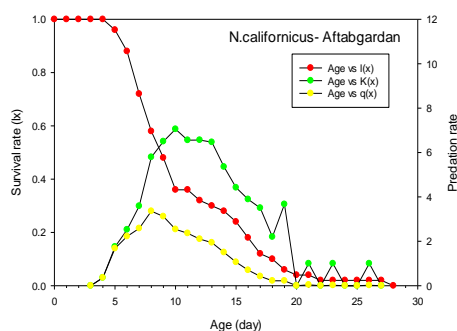
The age-stage predation rate ( $c_{xj}$ ) of *N. californicus* fed with sunflower, tamarix, common mallow pollens on *T. urticae* is shown in Fig. ۱ that illustrates the average number of consumed prey by a predator with age  $x$  in stage  $j$ . The curve related to predation rate in each age group-life stage indicates the different life stages separately and also the overlap between these stages. The age-stage predation rate was greatly influenced by pollen diet. In feeding on each of the studied pollens, the female developmental stage exhibited the highest age-stage predation rate compared to other developmental stages. The highest age-stage predation rate (۱۵) was associated with ۶-day-old female of *N. californicus* fed on tamarix pollen. However, as the female age increased, the age-stage predation rate decreased. In females that had fed on tamarix and common mallow pollens, the age-stage predation rate started at age of ۵ days, but in females that had fed on sunflower pollen, it started at age of ۶ days (Fig. ۱). Male adults fed tamarix pollen could show a higher age-stage predation rate than those fed other pollens, whereas when fed common mallow pollen, their age-stage predation rate was zero compared to other growth stages. In total, the highest number of prey eaten by males (۱۰ preys) was obtained when feeding on a tamarix pollen diet at ۱۷ days of age (Fig. ۱). Only under the tamarix pollen diet condition, the age-stage predation rate of *N. californicus* raised with increasing predator stage for *T. urticae* prey. Therefore, under these conditions, adults consumed more prey compared to immature stages (Fig. ۱). At sunflower pollen diet, immature stages showed the highest number of eaten prey (۸ preys) at ۵ and ۶ days of age (Fig. ۱).



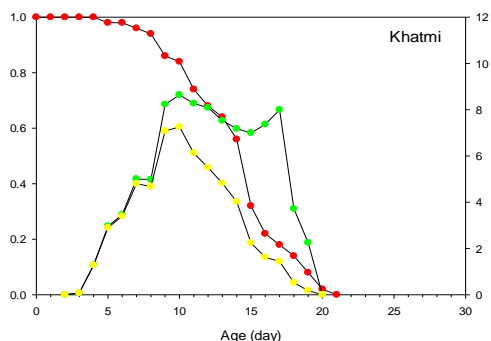


**Figure 1- The age-stage specific predation rate ( $C_{xj}$ ) of *Neoseiulus californicus* fed with sunflower, tamarix, common mallow pollens.**

The age-specific survival rate ( $l_x$ , the probability that a newborn will survive to age  $x$ ), the age-specific predation rate ( $k_x$ ), and age-specific net predation rate ( $q_x$ ) of *N. californicus* fed with sunflower, tamarix, and common mallow pollens were combined for all stages and are plotted in Fig. 2. The highest age-specific survival rate was observed at 0 and 1 days of age with feeding on tamarix pollen. Predatory mite *N. californicus* that fed on tamarix pollen had a higher age-specific survival rate with increasing age and also in adults compared to the other two pollens (Fig. 2). In sunflower pollen, the age-specific survival rate reduced rapidly to 37% from 0 to 10 days and then slowly decreased to 0% at the age of 24 days. In tamarix pollen, it diminished slowly to 54% from 0 to 12 days and then rapidly decreased to 0% at the age of 23 days. In common mallow pollen, survival rate reduced slowly to 91% from 0 to 8 days and then rapidly diminished to 0% at the age of 21 days (Fig. 2). The age-specific predation rate showed the average number of prey consumed by the predator at age  $x$ . In this study, the age-specific predation rate refers to the average number of *T. urticae* consumed by *N. californicus* at age  $x$ , which was examined by separately feeding on sunflower, tamarix, and common mallow pollens. Under the condition of feeding on tamarix pollen, the highest age-specific predation rate (0.8) was obtained at the age of 12 days, followed by the ages of 13, 14, and 15 days, respectively. Under the condition of feeding on common mallow pollen, the highest age-specific predation rate (0.9) was observed at the age of 10 days, followed by the ages of 9, 11, and 12 days, respectively. Under the condition of feeding on sunflower pollen, the highest age-specific predation rate (0.6) was at the age of 10 days, followed by the ages of 9, 11, 12, and 13 days, respectively. In terms of pollen type, the age-specific predation rate of *N. californicus* was in tamarix > common mallow > sunflower (Fig. 2). The age-specific predation rate curve is a simplified version of the age-stage specific predation rate curves, and by considering survivorship, the age-specific net predation rate can be specified. Under conditions of feeding on tamarix pollen, the highest age-specific net predation rate of *N. californicus* (0.9) was obtained at the age of 12 days. Under the condition of feeding on common mallow pollen, the highest age-specific net predation rate (0.6) was at the age of 10 days and under the condition of feeding on sunflower pollen, its maximum amount (0.3) was observed at the age of 8 days. Predatory mites *N. californicus* that fed on tamarix pollen had a higher age-specific net predation rate compared to those feeding on the other two pollens, even at older ages (Fig. 2).







**Figure 2-** The age-specific survival rate ( $L_x$ ), the age-specific predation rate ( $k_x$ ), and age-specific net predation rate ( $q_x$ ) of *Neoseiulus californicus* fed with sunflower, tamarix, common mallow pollens.

The results of the total age-stage predation rate for the predatory mite *N. californicus* (Fig. 3) indicated that all developmental stages responded more to feeding on tamarix pollen. Under conditions of feeding on all three pollens, female adults had a higher total age-stage predation rate compared to other developmental stages, and male adults had a lower value. So that the lowest total age-stage predation rate across all ages was for adult males feeding on common mallow pollen. Under conditions of feeding on tamarix pollen, the highest total age-stage predation rate (360) was observed for adult females at the age of 12 days and under conditions of feeding on common mallow pollen, the highest value (340) was for adult females at the age of 10 days. Under conditions of feeding on sunflower pollen, the highest total age-stage predation rate (120) was obtained for female adults at the ages of 9 and 10 days. After the age of 12 days, the total age-stage predation rate of female adults at all ages was higher in tamarix pollen than in common mallow pollen and in common mallow pollen than in sunflower pollen (Fig. 3).

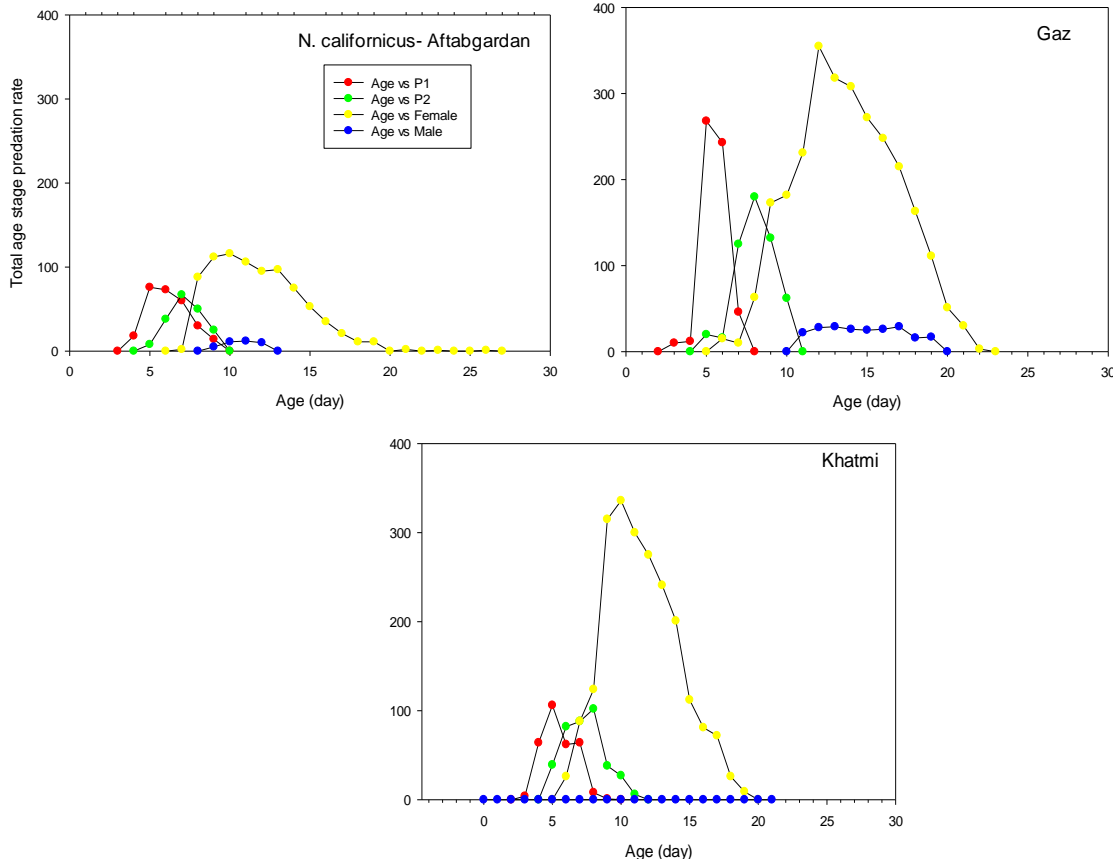


Figure ۳- Total age-stage predation rate of *Neoseiulus californicus* fed with sunflower, tamarix, common mallow pollens.

### Pollen chemical compositions

The results of pollen composition showed that the amount of total carbohydrates, fructose, sucrose, and glucose was higher in common mallow pollen (۲۳۸, ۳,۸۱, ۲,۸۶, and ۲,۸۵ mg g<sup>-1</sup>, respectively) than other pollens (Table ۴). The highest protein content (۳۳ mg g<sup>-1</sup>) was observed in tamarix pollen and the lowest was found in common mallow pollen (Table ۴). Sunflower pollen contained the highest lipid content (۵,۱٪) and the lowest content was found in common mallow pollen (Table ۴). Sunflower pollen had the highest amount of phenols and flavonoids (۱۵۵ mg g<sup>-1</sup> and ۹۶ mg g<sup>-1</sup>, respectively), and tamarix pollen contained the lowest amount of these compounds (Table ۴).

Table ۴- Chemical compositions in common mallow, tamarix, and sunflower pollens

Pollen	Total carbohydrate (mg g <sup>-1</sup> )	Fructose (% w/w)	Sucrose (% w/w)	Glucose (% w/w)	Total protein (mg g <sup>-1</sup> )	Lipid (% w/w)	Total phenol (mg g <sup>-1</sup> )	Total flavonoid (mg g <sup>-1</sup> )
Sunflower	۱۵۰±۰,۹۲b	۲,۴۰±۰,۰۱b	۱,۸۰±۰,۰۱b	۱,۷۹±۰,۰۱b	۳۲±۰,۱۱b	۵,۱±۰,۳a	۱۵۵±۰,۹۷a	۹۶±۰,۲۷a
Common mallow	۲۳۸±۰,۴۹a	۳,۸۱±۰,۰۱a	۲,۸۶±۰,۰۱a	۲,۸۵±۰,۰۱a	۳۰±۰,۳۴c	۳,۲±۰,۲۵c	۱۰۶±۰,۳۲b	۴۴±۰,۱۵b
Tamarix	۹۱±۰,۶۶c	۱,۴۶±۰,۰۱c	۱,۰۹±۰,۰۱c	۱,۰۸±۰,۰۱c	۳۳±۰,۲۵a	۴±۰,۲۸b	۸۵±۰,۱۹c	۳۶±۰,۳۳c

Means within a column with the same letter were not significantly different based on the Tukey test ( $\alpha=0\%$ ).

### Discussion

In greenhouses and/or fields experiencing a shortage or absence of natural prey, the survival, growth, and reproduction of predatory mites on alternative foods, such as plant pollens, is essential for the successful biological control strategies for these predators (McMurtry et al., ۲۰۱۳; Hashemi et al., ۲۰۲۱). In this study, to evaluate the suitability of common mallow, tamarix, and sunflower pollens as a sole or supplementary food source for predatory mite *N. californicus*, life table parameters were determined and compared with biological parameters of *N. californicus* fed with *T. urticae* and these pollens. By investigating six diets having pollens, this study improved the knowledge of the food source spectrum for rearing *N. californicus*. Our results indicated that *N. californicus* can feed and develop into adults on all tested diets. However, results from exclusive feeding of predatory mite *N. californicus* with tested pollens showed that under conditions of feeding on sunflower pollen, the growth and transformation of immature individuals of the predatory mite into adults occurred in a shorter time, but, by exclusive feeding on tamarix pollen, the completion of the predatory mite life cycle took a longer time. Also, the results indicated that *N. californicus* has a greater potential to survive, lay eggs, and complete its life cycle when fed on the tamarix pollen + *T. urticae* prey. It can be inferred that the positive effect of tamarix pollen on the growth and life cycle of *N. californicus* could be due to the high protein content in this pollen (Table ۴). In this regard, it has been reported that pollen protein content has an important role in nutritive value and consumer performance (Roulston and Cane, ۲۰۰۰). Also, differences in the nutritional value and morphological characteristics of pollen from various plants can affect the food supply required by mites, which in turn may lead to variations in the period of developmental stages and egg-laying rates in predatory mites tested on pollen (Goleva and Zebitz, ۲۰۱۳; Khanamani et al., ۲۰۱۷c; Pascua et al., ۲۰۲۰). Various studies have been conducted about the effect of plant pollens on the biological characteristics of phytoseiid predatory mites (Riahi et al., ۲۰۱۷; Rezaie, ۲۰۱۹). Other researchers have also studied the effect of pollen type and quality on the biological characteristics of the predatory mite *N. californicus* (Khanamani et al., ۲۰۱۷c; Soltaniyan et al., ۲۰۱۸). Rezaie (۲۰۱۹) stated that sunflower pollen is not suitable for completing the life cycle of the predatory mite *Neoseiulus barkeri*.

The average period of the egg stage of *N. californicus* on different pollen diets alone and in combination with *T. urticae* ranged from ۱,۵۲ to ۳,۷ days, and the period of the larval stage varied between ۱,۹۲ and ۲,۶۲ days. The duration of the egg stage of *N. californicus* when feeding on date palm and corn pollens has been reported to be ۲,۷ and ۲,۶۸ days, respectively (Khanamani et al., ۲۰۱۷b), and the duration of the larval stage of *N. californicus* when feeding on *T. urticae* + *Typha angustifolia* has been stated to be ۰,۵ days (Pascua et al., ۲۰۲۰). The difference in the present research compared

to the mentioned studies can be attributed to the different temperatures, data analysis methods, test accuracy, pollen type, prey type, and predation rate (Rezaie, ۲۰۱۹). In this study, when *N. californicus* was fed on *T. urticae* and the desired plant pollen, the longevity varied between ۱۳,۱۴ and ۱۹,۲۹ days for females and between ۱۳ and ۱۷,۵ days for males. The longevity of *N. californicus* females fed on date palm and corn pollens was ۳۷ and ۳۶ days, respectively (Khanamani et al., ۲۰۱۷b); while it was ۵۲,۳۸, ۴۳,۸۸, and ۴۱,۱۴ days when fed on pistachio, date palm, and pomegranate pollens, respectively (Hashemi et al., ۲۰۲۱). The longevity of *N. californicus* males was reported to be ۳۵,۶۱ and ۳۵,۲۹ days when fed on date palm and corn pollens, respectively (Khanamani et al., ۲۰۱۷b), and ۴۰,۳۶, ۳۸,۷, and ۳۶,۱۲ days when fed on pistachio, date palm, and pomegranate pollens, respectively (Hashemi et al., ۲۰۲۱). The shorter longevity of adults in this study compared to the mentioned studies can be attributed to variations in experimental temperatures, pollen types, prey types, and data analysis methods, as reported in other research (Rezaie, ۲۰۱۹).

Pre-ovipositional periods especially the total pre-ovipositional period (TPOP) have a main role in the intrinsic rate of increase. The longest total pre-ovipositional period was observed when the tamarix pollen+ *T. urticae* (and after that the tamarix pollen) was offered as the food source. When the sunflower pollen was offered as the sole food source, total pre-ovipositional period was not significantly different from those reared on common mallow alone. Deficiency or absence of primary essential nutrients (especially protein) in pollens for fecundity may be the source of such differences (Khanamani et al., ۲۰۱۷c). In this study, the protein content in sunflower and common mallow pollens was lower than that of tamarix pollen (Table ۴). The presence of *T. urticae* shortened total pre-ovipositional period of *N. californicus* on the sunflower pollen (and after that the common mallow pollen). Female phytoseiid mites lay eggs only when there is enough food for their offspring (Tsolakis et al., ۱۹۹۴). All diets in this study were able to support *N. californicus* fecundity. The highest average fecundity of *N. californicus* was obtained by feeding on sunflower + *T. urticae* (after that on tamarix + *T. urticae*). Exclusive pollen feeding did not make a difference in the fecundity of this mite; however, the fecundity was higher in exclusive feeding on tamarix pollen than in exclusive feeding on the other two pollens. The average fecundity of *N. californicus* feeding on *T. urticae* and cedar, pear, apricot and pistachio pollens was reported to be ۲۵,۱۱٪, ۲,۵۸, ۲,۸۲, ۱۳,۴۴, and ۳۰,۲۴ eggs per female, respectively (Soltaniyan et al., ۲۰۱۸). Researchers stated that *N. californicus* fecundity was higher when feeding on *T. urticae* and pollens (corn, date palm, and bee) than when the predatory mite fed only on pollens (Khanamani et al., ۲۰۱۷b). The results of the present study also showed the same result. Pollens from sunflower and hazelnut were less suitable as food sources, leading to the poor performance of *Amblyseius swirskii* (Goleva and Zebitz, ۲۰۱۳). Although the reproductive performance of the predator on the sunflower and common mallow pollens (in the absence of *T. urticae*) was low, because of their fitness for the retention of predator adults they can be used as a food source supplied during mass production of *N. californicus*. In the absence of natural prey, an alternative food source must be able to retain predatory mites over the long term rather than raise the capacity for producing eggs, because their over-abundance can cause the over-consumption of food resources and also an increment in cannibalism frequency (Schausberger, ۲۰۰۳). Therefore, sunflower and common mallow pollens may be appropriate for promoting the retention of *N. californicus* populations during periods when natural prey is lacking in plants.

The most preferred food source results in a higher intrinsic rate of increase and greater population growth. Under conditions of exclusive feeding on pollens in the present study, the intrinsic rate of increase for *N. californicus* was high only in tamarix pollen ( $۰,۱۱۲ \text{ day}^{-1}$ ), indicating the suitability of this pollen as an exclusive food for this predatory mite. However, adding the tested pollen to natural prey (*T. urticae*) increased the intrinsic rate of increase more. So that the intrinsic rate of increase in the diets of common mallow + *T. urticae* and tamarix + *T. urticae* ( $۰,۱۳۲$  and  $۰,۱۳۱ \text{ day}^{-1}$ , respectively) was higher than that of the other tested treatments. Similarly, *Neoseiulus cucumeris* (Oudemans) fed, developed, and reproduced better when it was provided with pollen (maize, sweet pepper, mungbean, cucumber, tomato, and rose) in combination with the prey (mold mite), compared to pollens offered alone (Sarwar, ۲۰۱۶). Plant pollens, as appropriate supplementary food sources, can positively influence the growth statistics of phytoseiid predatory mites. For example, the intrinsic rate of increase for *N. californicus* feeding on almond, date palm, sunflower, and castor bean pollens was reported to be  $۰,۱۲۹$ ,  $۰,۱۵۲$ ,  $۰,۱۲۳$ , and  $۰,۱۴۶ \text{ day}^{-1}$ , respectively (Yazdanpanah et al., ۲۰۲۱). In another study, the intrinsic rate of increase for *N. californicus* feeding on pistachio, date palm, and pomegranate pollens was estimated to be  $۰,۱۹۰$ ,  $۰,۱۸۴$ , and  $۰,۱۶۸ \text{ day}^{-1}$ , respectively, which was higher compared to other tested pollens. Also, pistachio and date palm pollens resulted in high finite rate of increase and net reproductive rate for *N. californicus* (Hashemi et al., ۲۰۲۱).



The intrinsic rate of increase, finite rate of increase, and net reproductive rate of *N. californicus* feeding on corn pollen in the presence of *T. urticae* ( $0.1409 \text{ day}^{-1}$ ,  $1.1513 \text{ day}^{-1}$ , and  $27.73$  offspring/individual, respectively) were higher than when the predatory mite fed on corn pollen and *T. urticae* separately (Khanamani et al., 2017b). These values in the above study were higher than the intrinsic rate of increase and net reproductive rate in all six diets in our study, which could be due to the pollen type and quality, rearing techniques, laboratory conditions, host plant used for rearing *T. urticae*, and data analysis method (Soltaniyan et al., 2018; Hashemi et al., 2021). The intrinsic rate of increase and net reproductive rate for the predatory mite *A. swirskii* were higher when feeding on almond pollen than on other pollens, and chemical analysis of pollens showed a higher nutritional value of almond pollen than the other two pollens (Riahi et al., 2017). Peach pollen diet produced the lowest the intrinsic rate of increase, finite rate of increase, and net reproductive rate and the longest preoviposition period of female. So it was inappropriate pollen for *N. californicus* (Hashemi et al., 2021). Taking only the three pollens tested in the present study into consideration, it specified that tamarix pollen due to its higher protein content was of higher nutritional value for *N. californicus* than the other pollens. This pollen resulted in shortest value of pre-adult development and preoviposition period of female, and the highest value of net reproductive rate, oviposition duration, fecundity, intrinsic rate of increase, and finite rate of increase, both in the absence and presence of *T. urticae*. Similar results were reported for *N. californicus* fed on date palm and pistachio pollens (Hashemi et al., 2021). Soltaniyan et al. (2018) stated that the shortest preoviposition period, longest oviposition period, and fecundity, as well as the highest intrinsic rate of increase, finite rate of increase, and net reproductive rate were on pistachio pollen, followed by apricot pollen, which was related to the higher nutritional value of these pollens for *N. californicus*. The sunflower pollen diet produced the lowest intrinsic rate of increase, finite rate of increase, net reproductive rate, and fecundity (despite the shortest preoviposition period of female) than the other two pollens in the absence of *T. urticae*, which indicated that this pollen was unsuitable for *N. californicus*. Similar results were reported for *N. californicus* fed on peach pollen (Hashemi et al., 2021). These differences may be related to pollen nutritional composition, pollen surface physiology (either by an impervious thick exine and/ or by the very long spines of the pollen surface), adaptation of mite mouthpart morphology to pollen morphology, and mite digestive metabolism (Khanamani et al., 2017b; Soltaniyan et al., 2018). In the diet of sunflower + *T. urticae*, shortest preoviposition period and highest fecundity were observed, while intrinsic rate of increase, finite rate of increase, and net reproductive rate had lower values in comparison to tamarix + *T. urticae* diet. On the other hand, higher fecundity compensated for longest preoviposition period in tamarix + *T. urticae* diet. In addition, intrinsic rate of increase, finite rate of increase, and net reproductive rate were higher in tamarix + *T. urticae* diet. Therefore, it is difficult to resist the result that tamarix pollen could be a more suitable food source for the growth and reproduction of *N. californicus* both in absence and presence of *T. urticae*.

Predation capacity of predatory mites may change with pollen availability (Rezaie and Montazerie, 2018). Therefore, this study investigated the predation rate of *N. californicus* with the availability of common mallow, tamarix, and sunflower pollens. The ability of *N. californicus* to suppress *T. urticae* varied depending on the pollen type, and the predation rate of *T. urticae* by *N. californicus* fed on tamarix pollen was the highest value compared to other pollens. In this regard, it has been reported that plant pollens can increase the efficiency of phytoseiid predatory mites to suppress the density of natural prey (e.g., *T. urticae*), which varies depending on the pollen type and phytoseiid species (Khanamani et al., 2017b). According to our results, under conditions of feeding on all three pollens, *N. californicus* female adults had a higher predation rate than other growth stages. However, adult females that fed on tamarix pollen had a higher predation rate. In fact, tamarix pollen enhanced the ability of *N. californicus* to reduce *T. urticae* populations. In this regard, Rezaie and Montazerie (2018) stated that the predation rate of *N. californicus* females on various growth stages of *T. urticae* was different among the predatory mite reared on corn, walnut, and date pollens and *T. urticae* eggs and the highest predation rate was related to *N. californicus* reared on date pollen. When *A. swirskii* was reared on almond pollen, the net predation rate, transformation rate, and finite predation rate were significantly higher (Ansari-Shiri et al., 2022). In another study, a diet consisting of *T. latifolia* pollen supported the development and reproduction of *N. cucumeris* for 20 consecutive generations without diminishing its predation capacity, making it an appropriate diet for the long-term rearing of *N. cucumeris* in augmentative biological control of tetranychid mites (Gravandian et al., 2022). The age-specific survival rate shows the survival of various development periods without considering the individual's differentiation. Predatory mite *N. californicus* that fed on tamarix pollen had a higher age-specific survival rate with increasing age and also in adults



compared to the other two pollens. In other words, in tamarix pollen, age-specific survival rate decreased slowly to 78% from 0 to 12 days. This could be due to the high protein content of tamarix pollen. It has been reported that the age-specific survival rate of *N. californicus* slowly decreased to 0% in pistachio and date palm pollens (Hashemi et al., 2021). The highest survival rate of *N. californicus* after the emergence of adult insects was observed on the diet of pomegranate, walnut, corn, saffron and olive pollens (Eini et al., 2022). Survival of *A. swirskii* was increased by feeding on a diet of apricot, soybean, sesame, and date palm pollens and was much more efficient than feeding on pest eggs alone (Fadaei et al., 2018).

Pollen composition affects its suitability for predatory mites (Khanamani et al., 2019c). This study revealed that the amount of total carbohydrates, fructose, sucrose, and glucose in common mallow pollen was higher than that of other pollens. The highest protein content was observed in tamarix pollen (and after that sunflower pollen). Protein seems to be the most effective nutrient for *N. californicus*, as the predatory mite, by exclusively feeding on tamarix pollen (having high protein), was able to complete its life stages and exhibited higher fecundity, net reproductive rate, finite rate of increase, and intrinsic rate of increase, while its performance was lower when feeding on sunflower pollen (having medium protein). Also, common mallow pollen caused the lowest performance in *N. californicus* due to its low protein content. Pollen protein content is one of the important indicators of nutritive quality as it is closely related to the performance of consumers (Roulston and Cane, 2000). The high protein content may also indicate that pollen is a highly suitable food source (Stanley and Linskens, 1974; Goleva et al., 2015). Riahi et al. (2016) reported that protein and sucrose play the most effective role in the nutritional value of food sources for *Typhlodromus bagdasarjani*. They also stated that almond pollen had the highest nutritional value for this predator due to its crude protein level above 25%, while corn pollen came in second place due to its moderate protein level (below 20%) and the highest sucrose content. The higher performance of predatory mites on pollens having greater protein content has been reported by Khanamani et al. (2019c). Studying the chemical compositions of 7 pollens (almond, corn, sunflower, date palm, bitter orange, bee pollen, and castor bean) showed that the highest lipid content was found in sunflower and castor bean pollens, while bee pollen had the highest amount of fructose and glucose (Riahi et al., 2016). In the present study, the highest amount of lipid was found in sunflower pollen, which was consistent with the above study. The lower performance of *N. californicus* on sunflower pollen can be due to the higher content of phenol and flavonoids. Whereas carbohydrates, proteins, lipids, and amino acids can be consumed as nutrients and digestion and metabolization should be unproblematic for phytoseiid mites, the detoxification of secondary compounds in pollen, like flavonoids, alkaloids, or saponins depends on the mite species mechanisms, such as metabolizing enzymes (Bonvehi et al., 2001; Goleva et al., 2015). Specifically, the esterases, multifunctional oxidases, or glutathione-S transferases, are responsible for food adaptations in herbivorous insects and detoxifying xenobiotics (Goleva et al., 2015). Additionally, certain pollens (e.g., maize pollen) may contain quercetin (a plant flavonoid.), a potent protease inhibitor that disrupts protein digestion and adversely impacts food conversion (Larsen, 1971; Goleva et al., 2015). Similarly, *Lilium martagon* pollen was called toxic pollen because of its plant secondary compounds (Goleva and Zebitz, 2013). To better understand the feeding of phytoseiid mites on plant materials, such as pollen, it is essential to know more about the chemical composition of pollen and the feeding physiology of these mites.

## Conclusion

The most striking findings from this study were that 1) the nutritional value of different pollens varies, and 2) different pollens have different effects on biological parameters and predation rates of *N. californicus*. Tamarix pollen resulted in the shortest value of pre-adult development and preoviposition period of females, and the highest value of net reproductive rate, oviposition duration, fecundity, intrinsic rate of increase, and finite rate of increase for *N. californicus* compared to other pollens, both in the absence and presence of *T. urticae*. Also, the availability of tamarix pollen increased the predation rate of *N. californicus*, which is beneficial for the control of *T. urticae*. This was due to the high nutritional value (protein content) of tamarix pollen. Therefore, tamarix pollen is a very suitable diet for *N. californicus*. Under conditions of feeding on sunflower and common mallow pollens (in the absence of *T. urticae*), *N. californicus* performance, especially reproductive was lower, but their adults were maintained in the long term. Therefore, sunflower and common mallow pollens may be suitable as a food source during mass production of *N. californicus* and to promote population maintenance





of this predator when natural prey (*T. urticae*) is scarce in crops. Thus, our findings provide important information in designing a comprehensive program for the conservation or mass production of *N. californicus* to control *T. urticae*.

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