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Synergistic effects of pollen grains on several vital life parameters of *Amblyseius swirskii* when preying upon *Tetranychus urticae*

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In this study, the efficiency of two pollens, Bird-of-paradise and Damask rose, was evaluated concerning the life table of the phyto-carnivorous predator *Amblyseius swirskii*, both alone and in combination with the spider mite *Tetranychus urticae* as a natural prey. Results showed that feeding on these pollens significantly increased fecundity and extended the oviposition period (40.29 eggs in 27.4 days, and 35.82 eggs in 21.41 days, respectively) compared to the prey alone (27.20 eggs in 18.40 days). The significantly highest pre-adult duration (6.714 days), adult longevity (71.45 days), fecundity (92.16 eggs/female), and oviposition days (50.3 days) were recorded in the treatment involving Bird-of-paradise + spider mite. The gross (*GRR*) and net (R_0) reproductive rates in both Damask rose + spider mite (41.99 and 36.49 eggs/individuals) and Bird-of-paradise + spider mite (51.7 and 46.9 eggs/individuals) indicated the highest values, with no significant difference between the two treatments. The significantly highest intrinsic rate ($r = 0.179$ day^{-1}) and finite rate of increase ($\lambda = 0.157$ day^{-1}) were measured in the treatment of Bird-of-paradise + spider mite. Therefore, the examined pollens induced *A. swirskii* to reproduce significantly for a longer duration. Additionally, each pollen, when mixed with the prey demonstrated additive effects on oviposition and population growth.

Keywords Biocontrol agent, Generalist predator, *Amblyseius swirskii*, *Tetranychus urticae*, Pollen, Mixed diet

Plants supply various nutrients to phyto-carnivorous arthropods such as honeydews, extracts, and pollen grains[1,2]. Among those nutrients, pollen is the main source of proteins, lipids, amino acids, vitamins, minerals, sterols, and other micronutrients[3–5]. Pollens also contain carbohydrates, including monosaccharides (sugars) and polysaccharides such as starch and cellulose. Monosaccharides such as glucose and fructose, along with starch, can be utilized as energy sources for the biosynthesis of tissues, proteins, and enzymes[6]. In addition, polysaccharides offer resistance to desiccation in pollen and provide structural support[7,8]. Thus, pollens can mainly affect life characteristics such as individuals' longevity[9] by influencing physiological metabolism[10,11] enhancing immunity[12] tolerating pathogens like bacteria[13] virus[14] and microsporidia[15] and reducing sensitivity to pesticides[16].

The nutritional composition of pollen grains varies widely among plant species[17–19]. Total carbohydrate content ranges from 13.92 to 36.59%, reducing sugars from 0.04 to 6.88%, non-reducing sugars from 7.31 to 18.88%, and starch from 2.42 to 22.40%. Protein content shows particularly high variability, ranging from 2.5 to 61%, with an average between 25% and 45%. Lipids range from 1.16 to 20.74%, and total ash from 2.35–4.90%[3,18,20]. *Phoenix dactylifera* pollen contains 28.80% moisture, 4.57% ash, 1.37% crude fiber, 20.74% fat, 13.41% carbohydrate, and 31.11% protein[21]. Among pollens collected by honeybees, protein content ranged from 7.27 to 7.47% in sedges (*Carex* sp.) to 21.82–24.90% in red dead-nettle (*Lamium purpureum* L.)[22].

Indeed, the quality of some pollen grains is better for the pollenophagous than others such as Christmas cactus *Schlumbergera* hybrid, spring crocus *Crocus vernus* Hill, castor bean *Ricinus communis* L., maize, and pine *Pinus sylvestris* L. ranging from highly to amply suitable. On the other hand, some other pollen grains are evaluated bad (e.g. bee pollen), negligible suitability (e.g. common hazel *Corylus avellane* L.), and even toxic or unsuitable for pollen feeders, such as martagon Lily *Lilium martagon* and amaryllis *Hippeastrum* sp., and rose of Sharon *Hibiscus syriacus* L[23]. Their undesirable effects may be due to their thick exine[24] very long spines on the pollen surface[25] repellent odors in the pollen pollenkitt[26] and/or toxic allelochemicals such as alkaloids, terpenes, or phenolics[27,28].

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Pollen grains are considered nutritious food for the establishment, increasing larval development, as well as enhancement of survival, and oviposition of general predatory insects and mites as biological control agents[29–31]. In addition, pollen could aggregate the predators' population in pollen plots to predate efficiently and prevent the predators from cannibalism[32]. Numerous studies have advised the usage of pollen grains for mass-rearing[33–37]. Also, several experiments reported that pollen can be a suitable alternative food when prey is rare or absent[38,39] and help the predators establish their population before enhancing the prey population[40,41].

According to habit and food spectrum, mites belonging to the family of Phytoseiidae are classified as specialists (type I, II) and generalists (type III, IV) with subtypes. Unlike type I and II phytoseiid species, type III and IV species receive pollen as a supplementary or alternative food source in practical biocontrol[42].

Among this important family, although examining pollen alone was the purpose of several studies[43–46] combining pollen with the main prey was also tested to evaluate the fitness and efficiency of the predators in the laboratory or the field. Adding pollen to cucumbers caused two species of predatory mites, *Iphiseius degenerans* Berlese and *Amblyseius limonicus*, to develop more rapidly and effectively suppress the thrips population[47]. In addition, the presence of pollen on strawberries increased the growth rate of *Amblyseius limonicus* Garman and McGregor, leading to improved control of *Trialeurodes vaporariorum* Westwood[48]. To manage *Tetranychus urticae* Koch, applying maize pollen improved the effectiveness of *Neoseiulus californicus* (McGregor)[49] and almond pollen enhanced the efficacy of *Amblyseius swirskii* Athias-Henriot[50].

Amblyseius swirskii Athias-Henriot is an important species of phytoseiid mite that was originally discovered in Algeria along the East Mediterranean coast. It was first described in relation to almond trees, specifically *Prunus amygdalus* L[51]. This species has a wide distribution, found not only to the Middle Eastern countries, but also in Southern Europe, central Africa, and North America[52]. As a generalist predator sub-type III-b, *A. swirskii* lives on glabrous leaves[42]. This species is associated with over 35 plant families, including ornamental plants, vegetable crops such as cucumbers, peppers, and eggplants, as well as cotton and fruit trees like apples, apricots, and citrus[53–56].

Previously, pollens of plants like pine[57] pistachio, date palm, pomegranate[58] maize[59] apricot, soybean, sesame, walnut[60] royal paulownia, silver birch[43] cattail[61] horse chestnut, crocus, hedgehog cactus[23] and apple[62] were recognized as proper for this phytoseiid species' biology and population parameters. In addition, under greenhouse conditions, the introduction of *A. swirskii* together with apple pollen application led to the best control of adults and immatures of western flower thrips, *Frankliniella occidentalis*[63]. On the other hand, according to Goleva, I. & Zebitz, C. P. W[23]. pollens of lilies, amaryllis, and shrub-althea were definitely incompatible with this predator; Pollens of sunflower, common hazel, and sweetgrass were less suitable as a diet source; And commercial bee pollen was not effective for the mite life-table parameters compared to pure pollen obtained from the plant species.

In this study, we evaluated the compatibility of pollen grains from the Bird-of-paradise (*Caesalpinia gilliesii*, Wall. ex Hook. D.Dietr., Fabaceae) and the Damask rose (*Rosa damascena* Mill., Rosaceae), alone and when combined with the two-spotted spider mite (*Tetranychus urticae* Koch) as natural prey on *A. swirskii*. *R. damascena* is one of the most well-known *Rosa* species, and some of its varieties are crucial for essential oil production and medicinal properties, as well as others widely cultivated as garden roses[64]. In Iran, the cultivation and consumption of this plant are significant, not only as an ornamental plant but also for extracting valuable rose water and rose oil[65,66]. *C. gilliessii* is native to dry and desert regions of Argentina and Uruguay but is now widely found in other tropical and arid regions worldwide[67]. The pollen from this plant species was a successful diet for the long-term rearing of *A. swirskii* even superior to maize pollen as a highly nutritious diet[68]. Although the efficiency of this pollen was studied as an alternative food, there was no information about its effect when supplemented with natural prey.

To examine the potential synergistic effect of each pollen grain, the biological characteristics and demographic traits of the phytoseiid mite were evaluated. Thus, several parameters involved longevity, development time of all life stages, fecundity, pre-oviposition period, oviposition period, age-specific fecundity, age-specific survival rate, age-stage specific survival rate, and age-stage specific fecundity, intrinsic rate of increase, net reproductive rate, gross reproductive rate, finite rate of growth, and mean generation time, were calculated based on the age-stage two-sex life table procedure.

Materials and methods

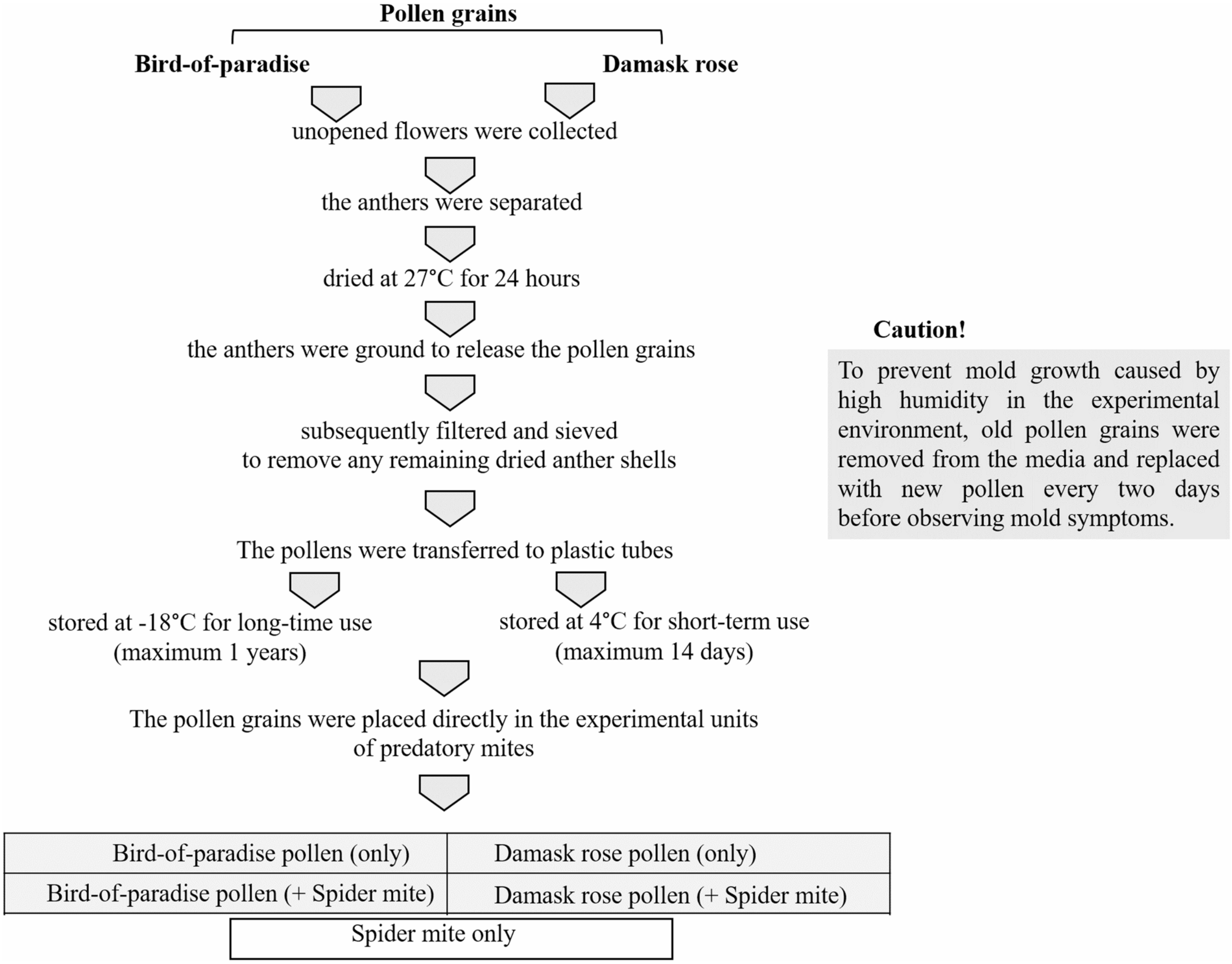
Pollen collection

Pollen grains of the Damask rose were collected from the plants in the village of Viduj, Isfahan Province, Iran. This village is well-known for the numerous fields devoted to planting *R. damascena*. Also, pollen grains of the Bird-of-paradise were collected from pesticide-free plants in the urban green spaces of Tehran city, Tehran province, Iran. Since the *C. gilliesii* plant is not native to Iran, only be cultivated in restricted locations. One of the most accessible places was the urban green spaces.

The pollens were dried at room temperature for 24 h, then transferred to plastic tubes and kept at 4 °C for short-term usage (maximum 14 days) or stored at −18 °C for long-term utilization[69] (Fig. 1).

Mite colonies

The initial *A. swirskii* population was obtained from the Department of Agricultural Entomology, Tarbiat Modares University, Tehran, Iran. The colony was reared in constant laboratory conditions at 25 ± 1 °C, 60 ± 5% Relative Humidity (RH), and a photoperiod of 16 L: 8D h. The rearing arena was a green plastic sheet (12 × 8 × 0.1 cm) on a water-soaked sponge (12 × 8 × 5 cm) inside a water-half-filled Plexiglas box (23 × 15 × 8 cm). All plastic sheet edges were enclosed with moist tissue paper following Walzer, A. & Schausberger, P[70]. to prevent mites from escaping. Some cotton filament was passed on the plastic sheet as a shelter and egg-laying position[71]. The stock colony was fed with eggs and pre-adult stages of *T. urticae*.



Caution!

To prevent mold growth caused by high humidity in the experimental environment, old pollen grains were removed from the media and replaced with new pollen every two days before observing mold symptoms.

Fig. 1. Preparation and preservation of pollen grains belonging to Bird-of-paradise and Damask rose.

The first population of *T. urticae* was collected from a cucumber greenhouse in Shahriar County, Tehran Province, Iran. After species confirmation, the colony was established on common bean, *Phaseolus vulgaris* L. The bean plants were planted sequentially in pots filled with coco peat, perlite, and peat moss (50:10:40) as a medium, in greenhouse conditions at 25 ± 1 ˚C, and 65 ± 5% RH. Once the plants reached the five-leaf stage, they were used for infestation by the prey mites. The infestation was carried out by attaching heavily infested leaves to the healthy potted plants, allowing the mites to easily disperse onto the new leaves.

Experimental units, and diets

Each experimental unit was designed similarly to the arena used for establishing the predator colony but on smaller-scale arenas of 3 × 3 × 0.1 cm located on top of a wet sponge (3 × 3 × 3 cm) placed in a small plastic box (7 × 5 × 4 cm) containing water. The edges of the green plastic sheets were restricted with moist tissue paper drenched in the water of the tray. In addition, a few threads of cotton were put on the center of each plastic sheet to provide a medium for oviposition.

The diet provided for each treatment was as follows: (a) Spider mite; (b) Bird-of-paradise pollen; (c) Damask rose pollen; (d) Bird-of-paradise pollen + Spider mite; (e) Damask rose pollen + Spider mite. Pollen grains were placed in the experimental arena with a sewing needle every two days. In treatments that included only spider mites or a combination of spider mites and pollen grains, 15 pre-adult individuals of *T. urticae* were introduced into each unit daily using a size 0000 brush.

Biological and life table studies

To assess the effects of the pollens on the predatory mites' biology and demographic parameters, the experiments were started with 50 cohort eggs for each treatment, and each individual was considered one replication. To obtain *A. swirskii* freshly laid eggs, 50 females and males were transferred from the stock colony to the new arenas. After 24 h, each freshly laid egg was put into one experimental unit. The experiments were performed in constant conditions with 25 ± 1 °C temperature, 60 ± 5% RH, and 16 L: 8D h, and each treatment was served with its diet. The development and survival of the pre-adult stages were monitored every 24 h. After adult emergence, each female was mated with a male from the same treatment, thus the number of eggs was counted besides the individuals' survivorship. When there were more females than males, or if the males died before the females, the males that developed from the colony were used as a supplement[72]. The daily observation continued until the death of all individuals in each treatment.

Statistical analysis

Data on *A. swirskii* life history and life table parameters were analyzed according to the age stage, two-sex life table theory[73] as well as the method described by Chi, H[74]. using the computer program TWOSEX-MSChart[75]. The bootstrap technique (described in a review article by Chi, H. et al.[76] with 100,000 samples embedded in the same program was used to estimate the variances and standard errors.

The biological parameters included longevity, duration of different life stages, fecundity, adult- and total-preoviposition periods (APOP and TPOP, respectively), and oviposition period. The other life parameters, for which value curves were drawn using Excel, included the age-stage specific survival rate (S_{xj}) (the possibility that a newborn individual will survive to age x and develop to stage j); the age-specific survival rate (l_x) (the probability that a newborn individual of both sexes will survive to age x); the age-specific fecundity (m_x) (the mean number of eggs produced per individual at age x); and the age-stage specific fecundity (f_{xj}) (the mean number of offspring that female individuals of age x at adult stage ($j = 5$) produced)[77]. Additionally, the life table parameters estimated using TWOSEX-MSChart were the net reproductive rate (R_0), gross reproductive rate (GRR), finite rate of increase (λ), intrinsic rate of increase (r), and mean generation time (T)[75]. The design of the experiments is shown step by step in Fig. 2.

Results

Survival and duration of different life stages

Eggs and larvae duration was significantly shorter in all pollen-based treatments compared to the spider mite-only diet (Table 1). Protonymph time was longest in the treatments fed Damask rose pollen + spider mite followed by spider mite. This stage duration in the other three treatments showed significantly the shortest time. On the other hand, the deutonymphs fed on Damask rose pollen had significantly the longest duration followed by Bird-of-paradise pollen + spider mite, Bird-of-paradise pollen, Damask rose pollen + spider mite, and spider

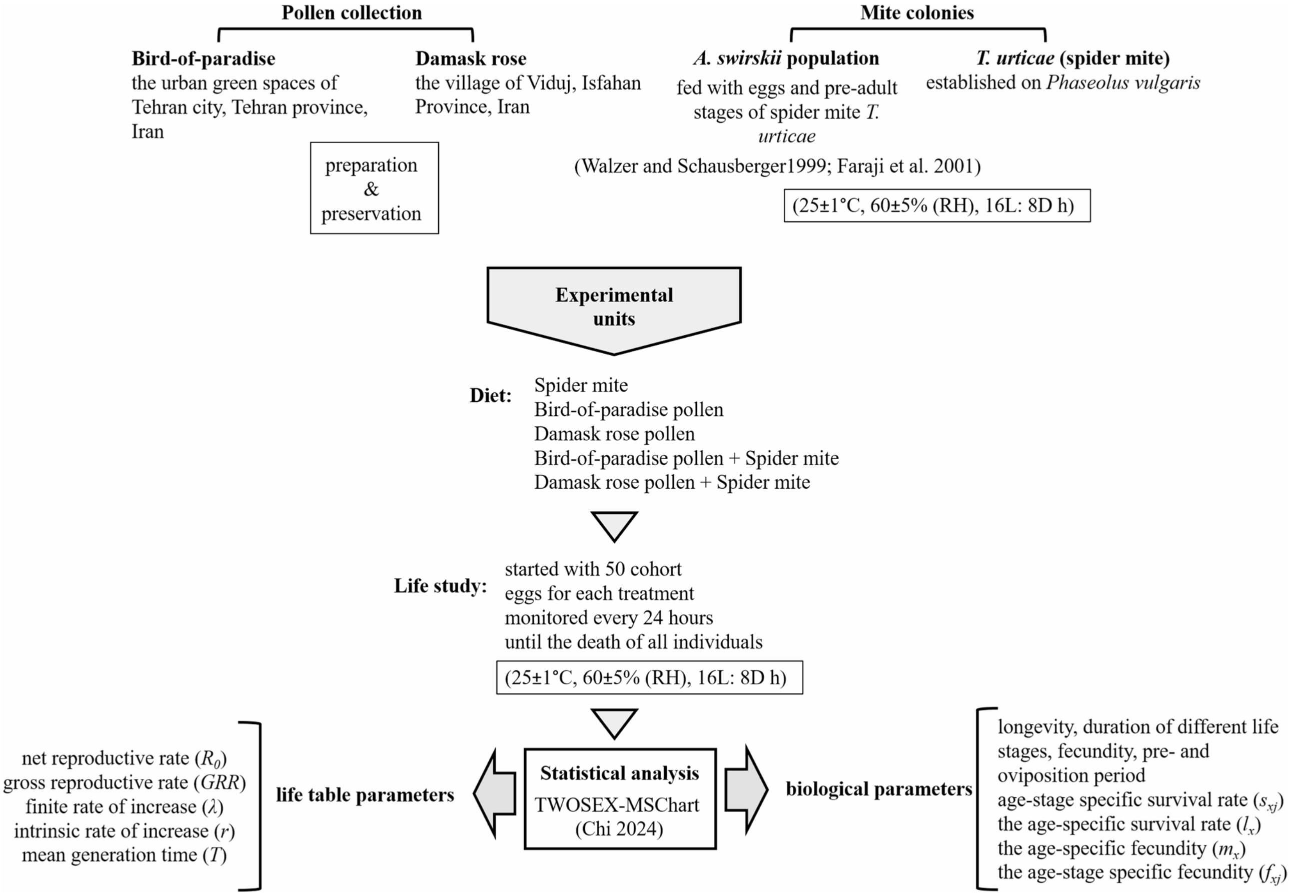


Fig. 2. Step-by-step life table experiments designed to test Bird-of-paradise and Damask rose pollen grains, both alone and in combination with spider mites, to measure the biological and ecological parameters of *Amblyseius swirskii*.

Duration Parameters	Damask rose	Bird-of-paradise	Damask rose + spider mite	Bird-of-paradise + spider mite	Spider mite
Egg (day)	1.49 ± 0.07^{a}	1.548 ± 0.077^{a}	1.44 ± 0.07^{a}	1.478 ± 0.074^{a}	2.185 ± 0.091^{b}
Larva (day)	1.647 ± 0.067^{a}	1.561 ± 0.098^{a}	1.612 ± 0.07^{a}	1.511 ± 0.074^{a}	1.148 ± 0.068^{b}
Protonymph (day)	1.5 ± 0.07^{c}	1.685 ± 0.075^{c}	2.063 ± 0.062^{a}	1.488 ± 0.076^{c}	1.852 ± 0.101^{b}
Deutonymph (day)	2.401 ± 0.073^{a}	2.027 ± 0.097^{bc}	2.021 ± 0.08^{c}	2.238 ± 0.074^{ab}	1.852 ± 0.101^{d}
Pre-adult duration (day)	7.045 ± 0.121^{ab}	6.811 ± 0.107^{bc}	7.149 ± 0.125^{a}	6.714 ± 0.113^{c}	7.112 ± 0.212^{a}
Pre-adult survival rate	0.882 ± 0.045^{a}	0.881 ± 0.05^{a}	0.94 ± 0.034^{a}	0.913 ± 0.041^{a}	1^{a}
Adult (day)	32.60 ± 0.783^{d}	41.51 ± 0.819^{c}	62.38 ± 1.037^{b}	71.45 ± 0.889^{a}	30.848 ± 1.76^{d}
Total longevity (day)	39.65 ± 0.798^{d}	48.32 ± 0.796^{c}	69.53 ± 1.033^{b}	78.16 ± 0.994^{a}	37.96 ± 1.747^{d}

Table 1. Duration parameters (± SE) of pre-adult and adult stages of *Amblyseius swirskii* fed with immature stages of the spider mite *Tetranychus urticae* as well as pollen grains of Bird-of-paradise and the Damask rose, alone/combined with the spider mite. ($P < 0.05$, paired-bootstrap test). The means (± SE) followed by different lowercase letters in the same row are comparisons among different treatments.

Reproduction parameters	Damask rose	Bird-of-paradise	Damask rose + spider mite	Bird-of-paradise + spider mite	Spider mite
Fecundity (eggs/female)	35.82 ± 1.475^{d}	40.29 ± 1.58^{c}	76.03 ± 2.372^{b}	92.16 ± 1.966^{a}	27.20 ± 2.276^{e}
Oviposition (day)	21.41 ± 0.832^{d}	27.4 ± 0.902^{c}	44.57 ± 1.181^{b}	50.3 ± 1.333^{a}	18.40 ± 1.519^{e}
APOP (day)	1.259 ± 0.085^{b}	1.9 ± 0.142^{a}	1.874 ± 0.091^{a}	1.391 ± 2.594^{b}	1.933 ± 0.203^{a}
TPOP (day)	8.408 ± 0.2^{b}	8.6 ± 0.231^{b}	8.958 ± 0.22^{b}	7.783 ± 0.196^{c}	9.069 ± 0.388^{a}

Table 2. Reproduction characteristics (± SE) of pre-adult and adult stages of *Amblyseius swirskii* fed with immature stages of the spider mite *Tetranychus urticae* as well as pollen grains of Bird-of-paradise and the Damask rose, alone/combined with the spider mite. ($P < 0.05$, paired-bootstrap test). The means (± SE) followed by different lowercase letters in the same row are comparisons among different treatments.

mite treatments. The total pre-adult duration in Damask rose pollen + spider mite, and spider mite treatments was illustrated as significantly longer than other treatments. However, the shortest duration was measured in the predators fed Bird-of-paradise pollen + spider mite. There was no observed significant mortality among treatments during the pre-adult stages. Adult longevity of mites fed on the Bird-of-paradise pollen + spider mite diet was significantly greatest among other treatments followed by those fed Damask rose pollen + spider mite, and Bird-of-paradise pollen diets. There was no significant difference between treatments fed Damask rose pollen and spider mite, which showed the shortest adult duration. The same trend was also calculated for total longevity (Table 1).

Reproductive periods and fecundity

The maximum and minimum fecundity were measured in the females fed Bird-of-paradise pollen + spider mite and spider mite, respectively. Indeed, the phytoseiids ingested Bird-of-paradise pollen + spider mite laid 3.38 times higher than those preyed on *T. urticae*. On the other hand, the Bird-of-paradise pollen + spider mite treatment females oviposited during the longest duration compared to other treatments (Table 2). Again, the females fed on spider mites reproduced during the shortest time. The total pre-oviposition period in mites fed on Damask rose pollen, Bird-of-paradise pollen, and Damask rose pollen + spider mite was significantly shorter than those fed Bird-of-paradise pollen + spider mite, and spider mite only. On the other hand, the total pre-oviposition time in the treatment fed on spider mites was significantly the longest. Females in the treatments involved Bird-of-paradise pollen, Damask rose pollen + spider mite, and spider mite only oviposited their eggs around 2 days after adulthood, while adult females in the treatments Damask rose pollen and Bird-of-paradise pollen + spider mite could lay their eggs sooner than others (Table 2).

Survival and fecundity curves

A. swirskii survived and oviposited successfully while feeding pollen grains, alone and in combination with the spider mite (Figs. 3, 4 and 5). There was up to 12% mortality when the pre-adult individuals fed on the pollens. Also, the mortality in both treatments fed pollens plus *T. urticae* was less than 10%. On the other hand, juvenile mortality in the predators fed on the spider mites was zero. (Fig. 3). All individuals belonging to the treatments fed Damask rose pollen as well as the spider mites died on the 53rd day. In addition, all mites fed Bird-of-paradise pollen solely died on the 57th day. However, the treatments fed on Damask rose pollen plus spider mites and Bird-of-paradise pollen combined with spider mites died on the 85th and 92nd days, respectively (Fig. 3). Mites in the combined diets started laying eggs from the 6th until the 83rd day in Bird-of-paradise pollen + spider mites, and from the 7th until the 81 st day in Damask rose pollen + spider mites (Fig. 3).

Variations in developmental rates among eggs, larvae, protonymph, and deutonymph caused some overlap between different stages (Fig. 4). The maximum number of deutonymphs was observed on the 6th day in the Damask rose pollen + spider mite treatment, but on the 5th day in the other treatments (Fig. 4).

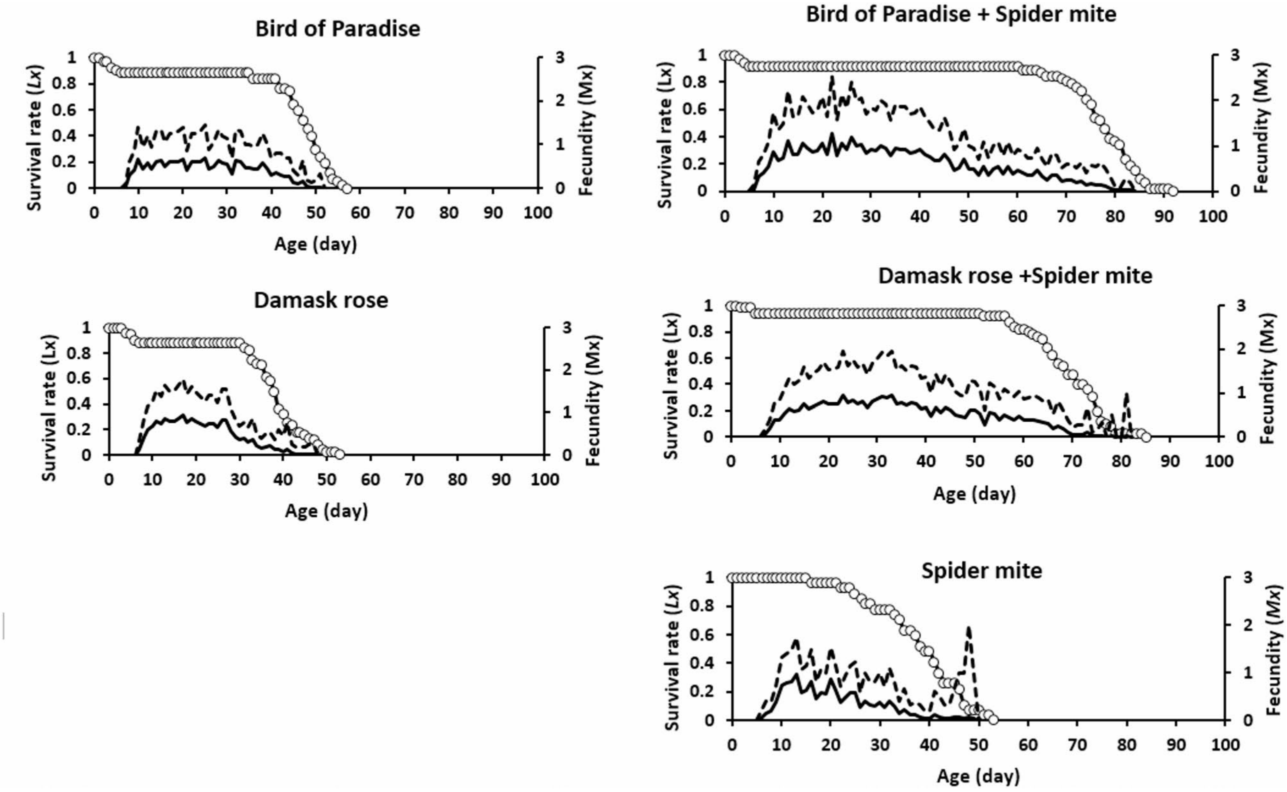


Fig. 3. Age-specific survival rate (l_x), age-stage specific fecundity (f_{xj}) and age-specific fecundity (m_x) of *Amblyseius swirskii* fed with immature stages of the spider mite *Tetranychus urticae* as well as pollen grains of Bird-of-paradise and the Damask rose, alone/combined with the spider mite.

According to Fig. 5, all females fed pollen-based diets lived longer than those that preyed upon spider mites only. In the treatment of Damask rose pollen + spider mites, females died 6 days after the males' mortality. On the other hand, the males in the treatment fed on spider mite died 2 days after the death of all females. Additionally, the survival rate of the females in all treatments from the 10th day to several days later was higher than the male survival rate. However, there was no difference between male and female survival rates in the predators fed on Damask rose pollen + spider mites from the 10th to the 56th day (Fig. 5).

Population growth parameters

All life table parameters of *A. swirskii* illustrated significant differences among different diets as shown in Table 3. The significantly highest intrinsic (r), and finite rate of increase (λ) were calculated in the treatments fed on Bird-of-paradise pollen + spider mite. However, both parameters in the phytoseiids fed with Bird-of-paradise pollen showed significantly the lowest values. The gross (*GRR*) and net reproductive rate (R_0) in Bird-of-paradise pollen + spider mite, and Damask rose pollen + spider mite, were significantly greater than other treatments. On the other hand, there was no significant difference among Damask rose pollen, Bird-of-paradise pollen, and spider mite treatments. The longest mean generation time (T) value was measured in mites fed on Damask rose pollen + spider mite, followed by two treatments of Bird-of-paradise pollen and Bird-of-paradise pollen + spider mite, but the significantly shortest duration was calculated in both treatments of Damask rose pollen and spider mite.

Discussion

This study examined the nutritional values of two types of pollen grains, each combined with the natural prey *T. urticae*, on the biology and life table parameters of *A. swirskii.* Additionally, the results were compared with the efficacy of the prey and each type of pollen alone.

This study confirmed that *A. swirskii* by feeding on Bird-of-paradise and Damask rose could survive, develop, and reproduce. Numerous studies have been dedicated to the population increase of the generalist predators including *A. swirskii* while feeding on different pollen grains belonging to diverse plant families[23,44,46,57–60,62,78–81]. It is reported that *A. swirskii* can establish, develop, and oviposit when fed on pollens of various species of the Rosaceae family[44,58,60,63,80,82]. Since generally pollens originating from plant species categorized at the same family level have similar results while offering to predatory mites as a food source[83]we expected that Damask rose pollen would be appropriate for the growth and development of *A. swirskii*. On the other hand, Kadkhodazadeh, F. et al.[58] were unable to rear *A. swirskii* with Damask rose pollens as a diet. In their study, the protonymphs

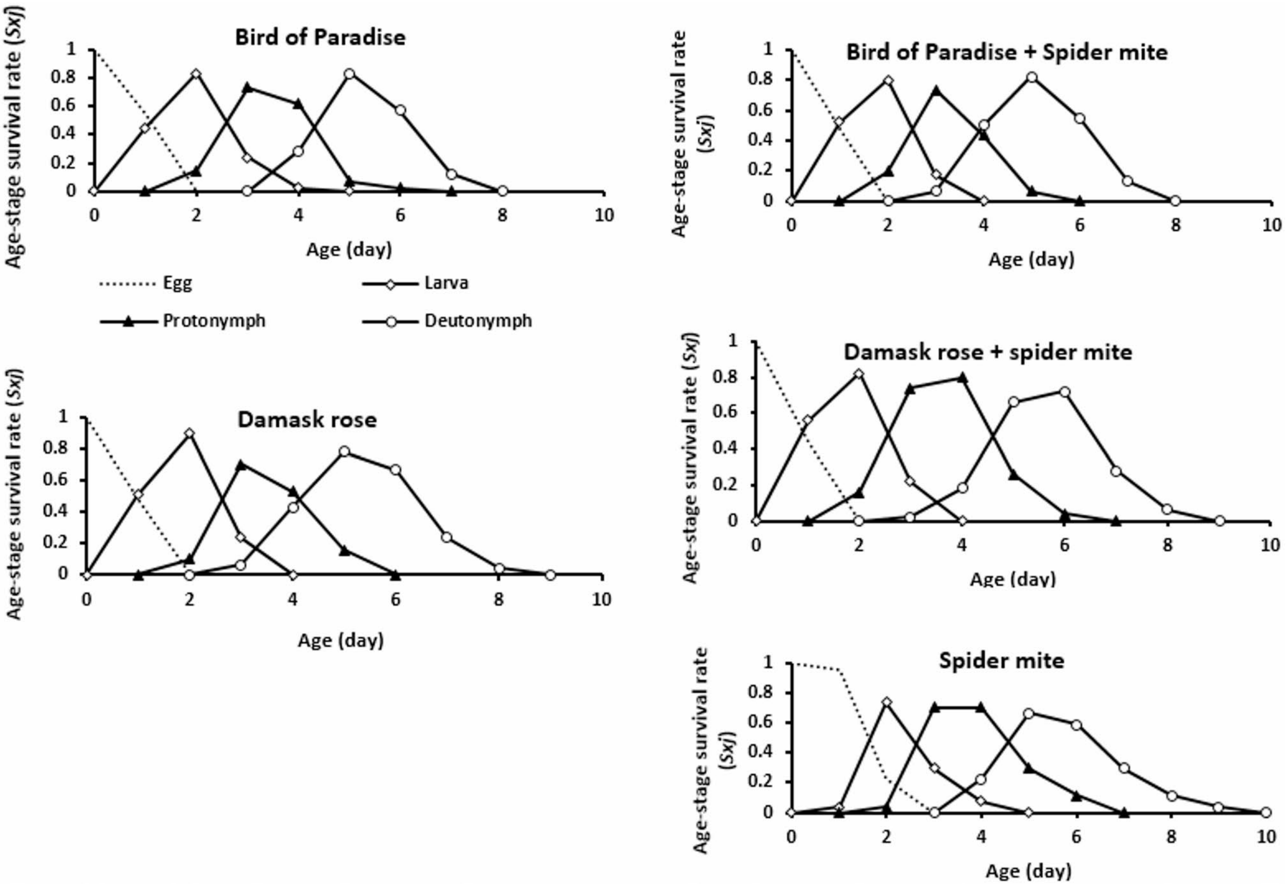


Fig. 4. Age-stage survival rate (S_{xj}) of pre-adult *Amblyseius swirskii* fed with immature stages of the spider mite *Tetranychus urticae* as well as pollen grains of Bird-of-paradise and the Damask rose, alone/combined with the spider mite.

and deutonymphs could not complete their life duration may be because of the toxic or volatile metabolites or pesticide residues applied on the flowers before pollen collecting.

Bird-of-paradise belongs to the Fabaceae family. Although the efficiency of pollen grains in this family is reported to be lower than that of other families, such as Poaceae[84]it is important to study their pollen quality more thoroughly due to the diverse species within the family. *C. gilliesii* is known for its fast growth and requires about 8 h of sunlight each day. It is also drought-tolerant[85]making it an excellent water-wise option for landscaping. Additionally, it has the potential to be successfully cultivated in various countries with ample sunny conditions. A multigenerational study using *C. gilliesii* pollen as an alternative food has introduced it as a promising diet for the population growth of *A. swirskii*[68].

Based on the results, *A. swirskii* fed on both pollen types, with approximately 90% of immature individuals surviving to reach adulthood and successfully reproduce. The durations of the egg, larvae, and protonymph stages in both treatments were nearly identical. Due to the shorter deutonymph period of the Bird-of-paradise pollen treatment, the total immature time in this treatment was also shorter. Since a diet with lower quality delays the development of an organism[86]Bird-of-paradise pollen could be considered more appropriate than the other one. Although females of this treatment started to oviposit 0.64 days later, they laid more eggs and had a longer oviposition duration compared to those fed on Damask rose pollen.

Pollen grains from plants such as cattail[80]pepper[87] (Kumar et al. 2014), maize[23,80,82]date palm[78,80]and almond[44,82] have been reported as suitable for the development and population growth of *A. swirskii*, playing a promising role in mass rearing and as alternative or supplementary food for field establishment of this phytoseiid mite. A comparison between these commercially important pollen grains and the pollens from Damask rose and Bird-of-paradise, based on several biological and ecological parameters, emphasizes that both pollens in the current study are appropriate for the survival and growth of the *A. swirskii* population. Differences in the bioecological values of these pollens may arise from various factors, including the plant species or cultivars, the experimental conditions, and the methods used to prepare and preserve the pollens.

If pollen from plants can be easily obtained from local sources or regional supplier, the production and release of *A. swirskii* could become more cost-effective and efficient[78]. The availability of the two plants, Damask rose and Bird-of-paradise, in sunny regions of countries including Iran, can be a positive point for their use as alternative or supplementary food.

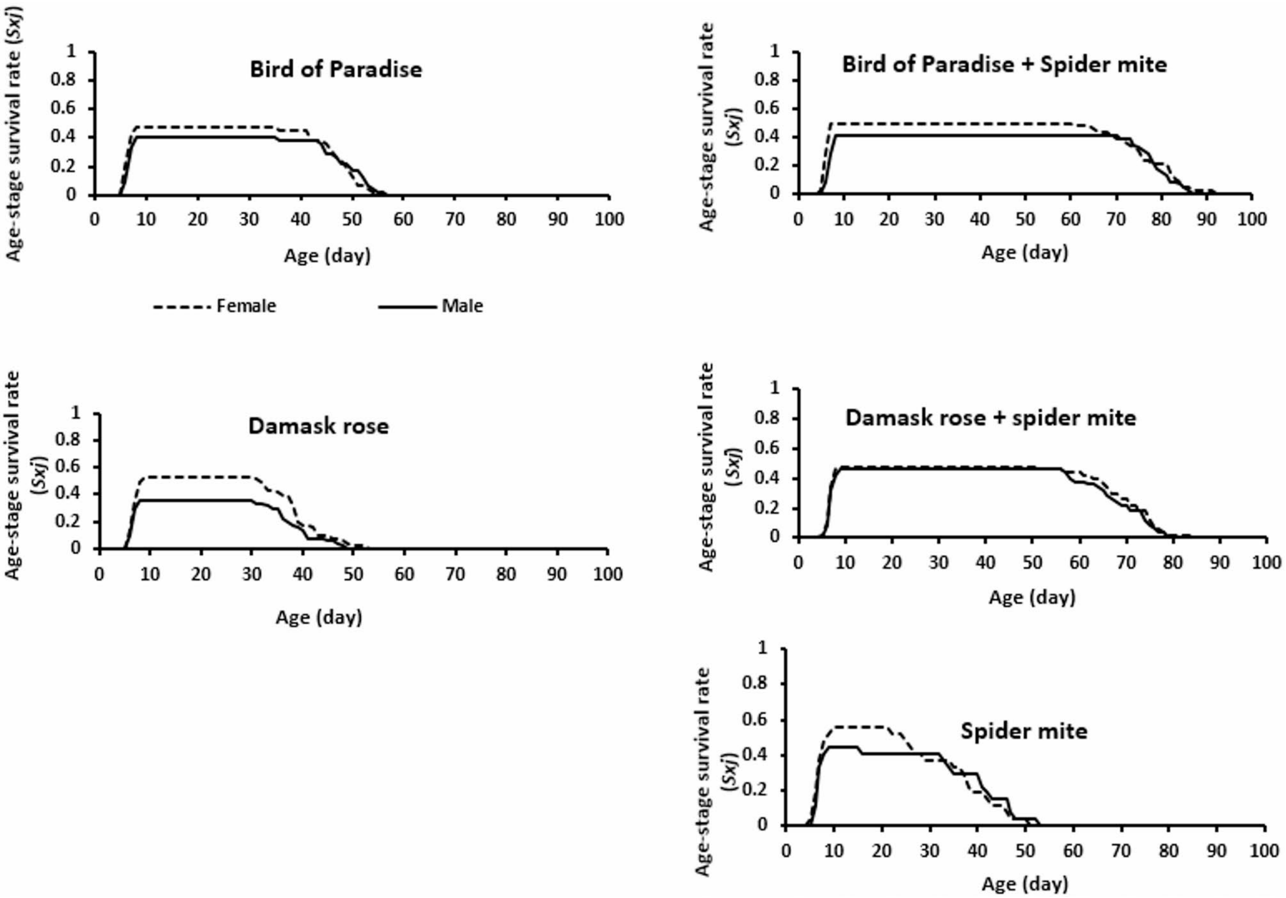


Fig. 5. Age-stage survival rate (S_{xj}) of adult *Amblyseius swirskii* fed with immature stages of the spider mite *Tetranychus urticae* as well as pollen grains of Bird-of-paradise and the Damask rose, alone/combined with the spider mite.

Parameters	Damask rose	Bird-of-paradise	Damask rose + spider mite	Bird-of-paradise + spider mite	Spider mite
GRR (eggs/individual)	23.46 ± 3.139^{b}	22.56 ± 3.563^{b}	41.99 ± 6.102^{a}	51.7 ± 7.497^{a}	19.12 ± 4.460^{b}
R_0 (eggs/individual)	18.97 ± 2.623^{b}	19.19 ± 3.188^{b}	36.49 ± 5.483^{a}	46.09 ± 6.909^{a}	15.12 ± 2.883^{b}
r (day^{-1})	0.168 ± 0.01^{ab}	0.146 ± 0.011^{b}	0.152 ± 0.009^{ab}	0.179 ± 0.011^{a}	0.156 ± 0.014^{ab}
λ (day^{-1})	1.183 ± 0.012^{ab}	1.157 ± 0.013^{b}	1.163 ± 0.011^{ab}	1.196 ± 0.013^{a}	1.169 ± 0.016^{ab}
T (day)	17.48 ± 0.333^{c}	20.15 ± 0.469^{b}	23.75 ± 0.637^{a}	21.35 ± 0.522^{b}	17.30 ± 0.806^{c}

Table 3. Demographic parameters (± SE) of *Amblyseius swirskii* fed with pollen grains of Bird-of-paradise and the Damask rose, alone/combined with immature stages of the spider mite *Tetranychus urticae.* ($P < 0.05$, paired-bootstrap test). The means (± SE) followed by different lowercase letters in the same row are comparisons among different treatments.

When Bird-of-paradise pollen was used with the spider mites as a mixture diet, the intrinsic rate of the mite population growth was calculated as the highest value among the treatments. This food significantly reduced premature duration, increased adult longevity, and enhanced fecundity during the longest time, compared to using Bird-of-paradise pollen alone and other diets. Several studies have indicated greater profits of mixed diets for predators' fitness[38,50,63,79,88].

Regardless of the superior effect of Bird-of-paradise pollen combined with *T. urticae*, the effect of Damask rose plus spider mite on the net reproductive rate (*r*) was not significantly different from this pollen alone and *T. urticae* as natural prey. The same outcome was obtained from the study conducted by Riahi, E. et al.[50] that this important life table statistic in *A. swirskii* consumed almond pollen alone and mixed with *T. urticae* was the same.

Indeed, pollen diets improve the development and reproduction of phyto-carnivorous mites when added to the animal diet by providing the essential nutrients sufficient for the mite's life parameters. At the same time, when the predator rears on only the pollen, it can also develop its biological parameters, thus the pollen as a consequence shows an important role in the life table but does not contain the essential nutrients sufficiently provided by the animal diet[38].

In a biological control system, supplementing pollen while releasing *A. swirskii* causes the pest reduction or elimination without needing multiple releases of the predator. This approach minimizes costs and saves time[89]. Both pollens in this study may potentially increase the predator's establishment at the early stages of the crop when pest abundance is still low[90–92]. This procedure could be highly efficient, especially for managing *T. urticae* before the population outbreak and producing dense webs, which is a hurdle to the generalist predators[93]. Exogenous Damask rose and Bird-of-paradise pollens can be applied through spraying, dusting, or point source applications in the crop[23]. The pollen supplementation in a system where prey is available increases the predatory reproductive capacity, followed by improving the pest control[94,95].

Conclusion

In conclusion, while *T. urticae* can be preyed on by *A. swirskii* as a biocontrol agent, both pollen grains of Bird-of-paradise and Damask rose have adequate nutritional values to guarantee phytoseiid development and reproduction when the prey is rare or absent. Each pollen has the potential to establish the predator in the field or greenhouse wherever it is possible to infest with *T. urticae*. Therefore, predators will be able to increase their population before the outbreak of the pest mites and control the pests by keeping their population at non-damaging levels. Moreover, in the presence of the mite pest, the efficiency of predators can be enhanced by the nutritional contents of the pollen grains from Bird-of-paradise and Damask rose. For selecting the best pollen, Bird-of-paradise is recommended as the most suitable supplementary food to promote the growth of the predatory population in areas affected by spider mites. This plant thrives easily, particularly in sunny areas. It is recommended to cultivate it in and around croplands with appropriate environmental considerations. During the flowering season, pollen can be collected and stored at low temperatures. When needed, this pollen can be sprayed onto the crops.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Author contributions

Faranak Kouros prepared the materials and collected and analyzed the data. Shima Rahmani (corresponding author) contributed to the study's conception, design, and data analysis and also wrote the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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