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Solid artificial diets for the phytoseiid predator *Amblyseius swirskii*

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Abstract *Amblyseius swirskii* (Athias-Henriot) (Acari: Phytoseiidae) is a key predator of a wide range of pests including thrips, whitefly and several mite pests. A number of artificial diets have been developed for this predator, but all of these are liquid, complicating their use in mass production. In the present study, we investigated the survival, development and reproduction of *A. swirskii* fed on several dry artificial diets: the tested diets were freeze dried forms of previously developed liquid meridic artificial diets supplemented with extracts of decapsulated cysts of *Artemia franciscana* Kellogg (Anostraca: Artemiidae) or with pupal hemolymph of Chinese oak silkworm *Antheraea pernyi* (Guérin-Méneville) (Lepidoptera: Saturniidae), and newly composed powdered meridic artificial diets supplemented with ground dry *A. franciscana* cysts or lyophilized pupal hemolymph of *A. pernyi*. Performance of the mite on the artificial diets was compared with that on cattail pollen (*Typha latifolia* L.). Developmental time of *A. swirskii* females offered lyophilized diets was significantly shorter than on powdered diets. Total fecundity was significantly higher for females fed on the lyophilized diets than for those maintained on the powdered diet with *A. franciscana*. Daily oviposition rates were similar on *T. latifolia* pollen and both lyophilized diets but lower on both powdered diets. The highest intrinsic rate of increase was observed when *A. swirskii* was fed on *T. latifolia* pollen (0.210 females per female per day), followed by the freeze dried diets enriched with *A. pernyi* and *A. franciscana* (0.195 and 0.184 females per female per day, respectively), and the lowest growth rates were observed on the powdered diets supplemented with *A. franciscana* and *A. pernyi* (0.159 and 0.158 females per female per day, respectively). In conclusion, the phytoseiid was able to effectively feed on solid, powdered artificial diets. Freeze-drying of liquid diets did not influence their value to support the development and reproduction of *A. swirskii*. For mass rearing purposes, these dry diets have several advantages over liquid ones, including more convenient application and storage. Furthermore, they are believed to have better potential for use as supplemental foods to sustain predatory mite populations in the crop after release.

Keywords *Amblyseius swirskii* · *Artemia franciscana* · *Antheraea pernyi* · Life table · Artificial diet · Augmentative biological control

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Introduction

In augmentative biological control programs, mass produced arthropod natural enemies are often released in high numbers to obtain pest suppression (Stinner 1977; Collier and van Steenwyk 2004). Optimizing mass production methods, for instance by developing cost effective factitious or artificial foods, may reduce the market price of biological control agents and improve their adoption by growers (De Clercq et al. 2014). The effectiveness of augmentative releases can also be enhanced by supplementing foods that increase survival and reproduction of the natural enemies after release, and arrest their emigration from the targeted area (Wade et al. 2008; Lundgren 2009).

The generalist predatory mite *Amblyseius swirskii* Athias-Henriot (Acari: Phytoseiidae) has been shown to be an effective biological control agent of whiteflies (Nomikou et al. 2002; Messelink et al. 2008), thrips (Messelink et al. 2006; 2008) and broad mites (van Maanen et al. 2010) in several greenhouse crops. The predatory mite also feeds on non-prey foods like pollen and honeydew (Momen and El-Saway 1993). The mass rearing procedures for *A. swirskii* are based on the use of storage mites, like *Carpoglyphus lactis* L. (Acari: Carpoglyphidae) and *Thyreophagus entomophagus* (Laboulbene) (Acari: Acaridae), as a food source (Bolckmans and van Houten 2006; Fidgett and Stinson 2008).

In a previous study we found that *A. swirskii* performed well on liquid artificial diets enriched with an extract of *Artemia franciscana* (Kellogg) (Anostraca: Artemiidae) cysts or with pupal hemolymph of the Chinese oak silkworm *Antheraea pernyi* (Guérin-Méneville) (Lepidoptera: Saturniidae), indicating the potential of these diets to sustain populations of the predator in the laboratory rearing as well as in the crop after release (Nguyen et al. 2014). However, liquid diets have certain disadvantages compared to solid diets in stickiness and in many cases a need for encapsulation (Morales-Ramos et al. 2014).

Solid artificial diets have mostly been developed for arthropods with chewing mouthparts (Morales-Ramos et al. 2014). However, Cohen (1998) noted that arthropods with extra-oral digestion, which include phytoseiid mites, can also feed on solid diets. The objectives of the present study were to determine developmental and reproductive parameters of *A. swirskii* fed on cattail pollen (*Typha latifolia* L.), on lyophilized forms of liquid artificial diets supplemented with an extract of decapsulated cysts of *A. franciscana* (ArF) or with pupal hemolymph of *A. pernyi* (AnF), and on solid artificial diets supplemented with powdered dry *A. franciscana* cysts (ArP) or with lyophilized pupal hemolymph of *A. pernyi* (AnP). The objective of this study was to design a solid artificial diet that can be used for the mass production of *A. swirskii* as well as to support its populations in the crop.

Materials and methods

Stock colony of *Amblyseius swirskii*

A stock colony of *A. swirskii* was initiated with specimens supplied by Biobest N.V. (Westerlo, Belgium) and was cultured in a growth chamber set at 25 ± 1 °C, 70 ± 5 % RH and a 16:8 h (L:D) photoperiod. Mites were reared on green plastic arenas (10×10×0.3 cm) (Multicel, SEDPA, France), placed on a wet sponge in a plastic tray containing water (Nguyen et al. 2013). The edges of the arenas were covered with tissue paper immersed in the water to provide moisture and deter the mites from escaping. Every two days mites were fed with fresh cattail pollen (*Typha latifolia* L.) that was supplied by Koppert B.V. (Berkel en Rodenrijs, The Netherlands) and stored at −18 °C. For the experiments, the pollen was thawed and kept in a refrigerator at 5 °C for max. one week. A small piece of black sewing thread was placed on the arenas to serve as an oviposition substrate. Every two days the eggs were collected and transferred to new arenas.

Preparation of artificial diet

Artificial diets ArF and AnF were prepared according to Nguyen et al. (2014). The diets were prepared based on 80 % w/w basic liquid artificial diet that was composed of 5 % honey (Meli N.V., Veurne, Belgium), 5 % sucrose (MP Biomedicals LLC, Illkirch, France), 5 % tryptone (Fluka Analytical, Sigma-Aldrich Co., St. Louis, USA), 5 % yeast extract (Duchefa, Haarlem, The Netherlands), 10 % fresh hen's egg yolk, and 70 % distilled water, supplemented with 20 % w/w extracts of decapsulated cysts of *A. franciscana* (ArF) or pupal hemolymph from the

Chinese oak silkworm *A. pernyi* (AnF), respectively. Pupal hemolymph of *A. pernyi* was provided in lyophilized form by the Guangdong Entomological Institute, Guangzhou, China. Decapsulated *A. franciscana* cysts were provided by the *Artemia* Reference Center of Ghent University (Ghent, Belgium) and originated from the Great Salt Lake (Utah, USA).

Diets ArF and AnF were frozen at −18 °C and lyophilized at −57.2 °C and 0.034 mbar for six days (VaCo 5-D freeze-dryer, Zirbus Technology Benelux B.V., Germany). Then the lyophilized diets were finely ground (particle diameter smaller than 0.3 mm) using a Bosch coffee grinder (Robert Bosch Hausgeräte GmbH, Munich, Germany), dispensed into 2 ml Eppendorf tubes and stored at −18 °C.

Artificial diets ArP and AnP were powdered diets composed of 16.6 % sucrose, 16.6 % tryptone, 16.6 % yeast extract, 6.7 % D-(+)-glucose anhydrous (MP Biomedicals LLC, Illkirch, France), 6.7 % fructose (Sigma Aldrich Chemie GmbH, Steinheim, Germany), 16.6 % egg yolk powder (Bouwhuis Enthoven BV, Raalte, The Netherlands), 0.13 % vitamin mix based on the composition of bovine liver (weight percentages: 25.4 % nicotinic acid, 4.9 % riboflavin, 0.5 % thiamine, 1.5 % vitamin B6, 12.4 % Ca-pantothenate, 1 % folic acid, 0.1 % biotin and 54.2 % vitamin C) (Vandekerkhove et al. 2006) and 20 % w/w powdered dry decapsulated *A. franciscana* cysts (ArP) or lyophilized pupal hemolymph of *A. pernyi* (AnP). The ingredients of both diets were finely ground (particle diameter smaller than 0.3 mm) using a Bosch coffee grinder. Next, the diets were dispensed into 2 ml Eppendorf tubes and stored at −18 °C.

Experimental setup

Eggs (less than 8 h old) were transferred individually from the *A. swirskii* colony to rearing microcosms that were modified from Munger cells as described by Ogawa and Osakabe (2008) and Nguyen et al. (2013) and offered *T. latifolia* pollen or one of the artificial diets. All foods were supplied ad libitum. The foods were offered from the larval stage of the predator on and refreshed every two days. After they had been taken out of the freezer, the diets were kept in a refrigerator at 5 °C for max. one week. To obtain data on the duration of immature development of *A. swirskii* and on mortality and escape rates, observations were made every 24 h until all individuals had reached adulthood. The developmental stage of each individual was determined based on the presence of exuviae in the cells. After completing immature development, each female was paired with a male that was reared on the same diet as the female. Males that died during the experiment were replaced with males that had been maintained on the same diet. Adults were observed daily to determine the preoviposition and oviposition period, longevity and fecundity. Progeny from females of the same age were transferred to new cells and fed on the same diet as their parents in order to determine the offspring sex ratio. Mites that escaped or died as a result of manipulation were excluded from data analysis. These escape and death rates did not differ among treatments and varied between 11 and 18 % ($\chi^2 = 0.730$, df = 4, $P = 0.948$; Probit test). The experiments were done in a growth chamber at 23 ± 1 °C, 65 ± 5 % RH and a 16:8 h (L:D) photoperiod.

Life table parameters

The intrinsic rate of increase (r_m) was calculated according to the formula of Lotka (1907) and Birch (1948):

$$\sum l_x m_x e^{-r_m x} = 1$$

where x equals the female age (days), l_x is the age specific survival of the females at age x and m_x is the number of daughters produced per female at age x. The latter parameter is obtained by multiplying the mean number of eggs laid per female by the proportion of female offspring produced at age x. The Jackknife procedure was used according to Meyer et al. (1986) and Hulting et al. (1990) to calculate the standard error of r_m. Other parameters calculated (Maia et al. 2000) were the generation time T, i.e. mean time span between the birth of individuals of a generation and that of the next generation (days),

$$T = \frac{\sum x l_x m_x}{\sum l_x m_x}$$

and the net reproductive rate, R_0, i.e. the mean number of female offspring produced per female

$$R_0 = \sum l_x m_x$$

Statistical analysis

Data were subjected to statistical analysis (IBM SPSS Statistics, Ver. 21) to evaluate the effect of diet on the developmental time, preoviposition and oviposition period, daily and total oviposition, and adult longevity of *A. swirskii*. When a Kolmogorov–Smirnov test indicated that means were normally distributed, the parameter was analysed using a one-way analysis of variance (ANOVA). If a Levene test indicated heteroscedasticity, a Tamhane test was used instead of a Tukey test. When means were not normally distributed, a nonparametric Kruskal–Wallis ANOVA was used and means were separated using Mann–Whitney U tests. Immature survival rates and sex ratios were compared by means of a logistic regression. This regression is a generalized linear model using a probit (log odds) link and a binomial error function. Each test consists of a regression coefficient that is calculated and tested for being significantly different from zero, for which *P* values are presented (McCullagh and Nelder 1989). In all tests, *P* values smaller than or equal to 0.05 were considered significant.

Results

Immature survival of *A. swirskii* did not differ among diets ranging from 98.2 to 100 % ($\chi^2 = 0.00$, df = 4, $p > 0.999$). Development times of both *A. swirskii* females and males were significantly affected by diet (Table 1). Females fed on *T. latifolia* pollen developed significantly faster to adulthood than those fed on the other diets. Development times of males offered *T. latifolia* pollen or both lyophilized diets (ArF and AnF) were shorter than of those given the powdered diets (ArP and AnP).

Diet significantly influenced the duration of the preoviposition period (Table 2). Females fed on *T. latifolia* pollen or AnF had significantly shorter preoviposition periods than those fed on ArF, ArP or AnP. Oviposition period of females did not differ among diets and ranged between 22.4 to 25.9 days. *Amblyseius swirskii* females reared on AnF lived significantly longer than those reared on *T. latifolia* pollen. Oviposition rates of *A. swirskii* on *T. latifolia* pollen, and both lyophilized diets were significantly higher than those of their counterparts on the powdered diets. However, total number of eggs laid during the females' lifetime did not differ among *T. latifolia* pollen and the powdered diets. Diet had no influence on the sex ratio of offspring with a proportion of females ranging from 0.72 to 0.80.

Table 1 Development time (days) of *Amblyseius swirskii* fed on *T. latifolia* pollen or different solid artificial foods

Diet	Developmental duration (days)[a]			
	Females	n	Males	n
T. latifolia	6.14 ± 0.11a	35	5.90 ± 0.18a	20
ArF	6.97 ± 0.16b	35	6.25 ± 0.17a	16
AnF	6.59 ± 0.15b	37	6.11 ± 0.17a	19
ArP	8.09 ± 0.08c	34	7.92 ± 0.08b	13
AnP	7.97 ± 0.11c	32	7.71 ± 0.09b	28
χ^2	94.321		64.775	
df	4		4	
P	<0.001		<0.001	

n Number of tested individuals

[a] Mean ± SE; means within a column followed by the same letter are not significantly different ($P > 0.05$), according to Mann–Whitney U test; χ^2-, df- and *P*-values refer to Kruskal–Wallis ANOVAs. ArF or AnF: freeze-dried liquid artificial diet supplemented with *A. franciscana* cysts or with pupal hemolymph of *A. pernyi,* respectively; ArP or AnP: basic powdered diet supplemented with powdered *A. franciscana* cysts or lyophilized pupal hemolymph of *A. pernyi,* respectively

Differences in developmental and reproductive characteristics were reflected in life table statistics. Net reproductive rates (R_0) of *A. swirskii* fed on *T. latifolia* pollen, or on the lyophilized diets were significantly higher than those of predators fed on both powdered diets (Table 3). Generation time (*T*) was significantly shorter for females offered *T. latifolia* pollen versus the other diets. Finally, the intrinsic rate of increase (r_m) of the predator was highest on *T. latifolia* pollen, followed by the lyophilized diets, and lowest on the powdered diets.

Discussion

Artificial diets for carnivorous arthropods can have a consistency ranging from liquid to solid, depending mostly on two factors: water content and molecular cohesion (Morales-Ramos et al. 2014). Artificial diets have been developed for a number of phytoseiid mites, with varying success (McMurtry and Scriven 1966; Kennett and Hamai 1980; Oloo and Amboga 1987;

Table 2 Reproduction and longevity of *Amblyseius swirskii* fed on *T. latifolia* pollen or different solid artificial foods

Diet	n	Preoviposition period (days)[a]	Oviposition period (days)[a]	Female longevity (days)[a]	Oviposition rate (eggs per female per day)[a]	Total number of eggs (eggs per female)[a]	Female proportion of the progeny[a]
T. latifolia	31	2.35 ± 0.09a	22.39 ± 1.21a	36.35 ± 2.36b	1.57 ± 0.04a	34.29 ± 1.40ab	0.78 ± 0.01a
ArF	30	2.97 ± 0.16b	24.73 ± 1.15a	44.73 ± 2.16ab	1.49 ± 0.03a	36.37 ± 1.53a	0.80 ± 0.02a
AnF	31	2.55 ± 0.14a	24.06 ± 1.60a	45.90 ± 2.42a	1.59 ± 0.05a	36.97 ± 1.87a	0.79 ± 0.02a
ArP	28	3.71 ± 0.09c	25.43 ± 1.18a	41.07 ± 1.99ab	1.25 ± 0.04b	30.75 ± 0.83b	0.76 ± 0.03a
AnP	28	3.71 ± 0.09c	25.89 ± 1.34a	39.14 ± 1.82ab	1.19 ± 0.05b	30.79 ± 1.94ab	0.72 ± 0.04a
χ^2/F		71.183	1.100	3.354	20.185	3.503	4.626
df		4	4, 143	4, 143	4, 143	4, 143	4
P		<0.001	0.359	0.012	<0.001	0.009	0.328

n Number of tested females

[a] Means ± SE; means within a column followed by the same letter are not significantly different ($P > 0.05$) according to Mann–Whitney U test (preoviposition period), Tukey test (oviposition period, female longevity, oviposition rate), Tamhane test (total number of eggs) or Probit (Wald Chi^2) test (female proportion of progeny); χ^2-, df- and *P*-values refer to Kruskal–Wallis ANOVAs, and F-, df- and *P*-values refer to one-way ANOVAs. ArF or AnF: freeze-dried liquid artificial diets supplemented with *A. franciscana* cysts or with pupal hemolymph of *A. pernyi,* respectively; ArP or AnP: basic powdered diet supplemented with powdered *A. franciscana* cysts or lyophilized pupal hemolymph of *A. pernyi,* respectively

Table 3 Life table parameters of *Amblyseius swirskii* fed on *T. latifolia* pollen or different solid artificial foods

Diets	n	Net reproductive rate (R_0, females per female)[a]	Generation time (T, days)[a]	Intrinsic rate of increase (r_m, females per female per day[a]
T. latifolia	31	25.93 ± 1.04a	15.49 ± 0.15a	0.210 ± 0.001a
ArF	30	28.77 ± 1.25a	18.23 ± 0.24b	0.184 ± 0.002c
AnF	31	28.97 ± 1.41a	17.23 ± 0.26c	0.195 ± 0.001b
ArP	28	22.00 ± 0.54b	19.46 ± 0.18d	0.159 ± 0.001d
AnP	28	21.00 ± 1.02b	19.34 ± 0.22d	0.158 ± 0.002d
F		11.012	60.705	232.645
df		4, 143	4, 143	4, 143
P		<0.001	<0.001	<0.001

n Number of tested females

[a] Means ± SE; means within a column followed by the same letter are not significantly different ($P > 0.05$) according to Tamhane test (net reproductive rate) or Tukey test (generation time, intrinsic rate of increase); F-, df- and *P*-values refer to one-way ANOVAs. ArF or AnF: freeze-dried artificial diet supplemented with *A. franciscana* cysts or with pupal hemolymph of *A. pernyi,* respectively; ArP or AnP: basic powdered diet supplemented with powdered *A. franciscana* cysts or lyophilized pupal hemolymph of *A. pernyi,* respectively

Abou-Awad et al. 1992; Ogawa and Osakabe 2008; Nguyen et al. 2013; 2014). All of these artificial diets were liquid in form. Solid artificial diets have a number of advantages over liquid and semi-liquid diets, both in the laboratory rearing and when applied as supplemental foods in the crop. These include non-stickiness and the possibility of direct presentation without the need for encapsulation (Morales-Ramos et al. 2014). Lower water content of solid diets limits microbial contamination and allows easier long term storage. When applied as a supplemental food in the field, solid artificial diets are easier to distribute in the crop [e.g. by blowers designed to distribute pollen or eggs of *Ephestia kuehniella* (Zeller) (Lepidoptera: Pyralidae)] and are expected to result in lower soiling of the plant surface and thus to interfere less with plant physiology and crop quality.

Previous studies demonstrated the potential of liquid artificial diets supplemented with pupal hemolymph of *A. pernyi* or with an extract of *A. franciscana*

cysts to support the development and reproduction of *A. swirskii* (Nguyen et al. 2013; 2014). The objective of the present study was to develop an adequate solid diet as a food for the mass rearing or for application in the field. Our results indicate that *A. swirskii* performed well, both in terms of its development and reproduction, when exclusively fed on various powdered solid artificial diets, although its performance did not match that on *T. latifolia* pollen.

Among the four artificial diets tested, the highest intrinsic rate of increase of *A. swirskii* (0.195 females per female per day at 23 °C) was recorded on freeze-dried artificial diet AnF, a meridic diet enriched with pupal hemolymph of *A. pernyi*. Although lower than on *T. latifolia* pollen in the present study, this growth rate exceeds the values reported for *A. swirskii* feeding on several natural prey, including the two spotted spider mite *Tetranychus urticae* Koch (Acari: Tetranychidae) (0.167 at 26 °C) (El-Laithy and Fouly 1992), the western flower thrips *Frankliniella occidentalis* (Pergande) (0.056 at 25 °C) and onion thrips *Thrips tabaci* (Lindeman) (Thysanoptera: Thripidae) (0.024 at 25 °C) (Wimmer et al. 2008), and the eriophyoid fig mites *Aceria ficus* (Cotte) (0.155 at 29 °C) and *Rhyncaphytoptus ficifoliae* Keifer (0.122 at 29 °C)(Abou-Awad et al. 1999). Interestingly, the growth rate on AnF is also superior to that on the dried fruit mite *C. lactis*, a factitious prey which is routinely used in the mass production of *A. swirskii* (0.175 at 23 °C) (Nguyen et al. 2013). Arguably, caution is warranted when comparing absolute values of intrinsic growth rates among studies as they may be influenced by differences in climatic conditions, experimental methods, and calculation of estimates. Interestingly, intrinsic growth rates of *A. swirskii* in our study are closely correlated with oviposition rates, with about 90 % of the variation in growth rates being explained by oviposition rates. This confirms the observations by Janssen and Sabelis (1992) who suggested that an assessment of peak oviposition may be sufficient to estimate the reproductive performance of predatory mites, precluding the necessity to perform full life table studies.

The fecundity of females fed on the freeze-dried liquid artificial diets ArF and AnF was similar to that on *T. latifolia* pollen and higher than that on the powdered diets ArP and AnP, which were both composed of solid basic ingredients. Parameters of development and reproduction of females fed on lyophilized diets were similar to those on the original liquid versions of the diets as reported by Nguyen et al. (2014), indicating that the freeze-drying process did not influence the nutritional quality of the diets and that the predator handled the solid forms as effectively as the liquid forms. This confirms previous findings with diets for predators and plant bugs, which have also indicated that the nutritive qualities and palatability are retained after freeze-drying and rehydration of certain insect diets (Cohen 2004). Freeze-dried diets have several practical advantages over liquid diets related to storage, shipment and handling. For instance, a freeze-dried medium may be stored at room temperature for months with no loss of nutritional quality (Cohen 1999). The freeze dried diets used in our study proved to be highly hygroscopic and quickly reverted to a semi-liquid form. This liquefaction process may have been accelerated by the high relative humidity in the Munger cells, which was always in excess of 85 %, and may thus be slower under practical conditions. On the one hand, the partial liquefaction of these freeze dried diets may be beneficial as it may facilitate feeding by the mites. On the other, however, it may limit their practical applicability: for instance, when not replaced on a regular basis like in the present study, such diets may be more prone to microbial degradation and may thus require the addition of antimicrobial agents. Further, the freeze-drying process also increases the cost of the artificial diets.

The availability of an adequate artificial diet would preclude the necessity to maintain parallel cultures of prey mites in the mass production system, resulting in less labour costs and lower health risks for workers in the production environment (i.e. potential allergy problems related to the use of storage mites). Even when such artificial diets appear suboptimal as compared to storage mites in terms of predator population growth rates, they could be used in part of the production cycle of the phytoseiids. Most ingredients of the presented diets are relatively inexpensive and easily accessible on the market. Based on economies of scale, prices may further be reduced if these diets are produced at a larger scale. In order to enhance cost effectiveness as compared to the liquid diets previously designed by Nguyen et al. (2014) and their lyophilized forms tested here, the powdered diets ArP and AnP were created by replacing the liquid ingredients of the original formulations in Nguyen et al. (2014) by powdered solid ingredients. The honey was

replaced with sucrose, glucose and fructose, fresh egg yolk was replaced with spray-dried egg yolk, and a vitamin mix was added. However, *A. swirskii* fed on the powdered diets had significantly longer developmental times and lower oviposition rates and intrinsic rates of increase than those reared on the freeze dried diets. These differences in performance of the mite can be explained in part by differences in the nutritional profiles of the corresponding diets. For instance, honey contains other compounds than sugars, like vitamins, minerals and amino acids, which may have a positive impact on the development and reproduction of *A. swirskii*. Guardiola et al. (1995) found that fatty acids undergo considerable oxidation during spray-drying of egg. Therefore, the nutritive value of egg yolk powder may be lower than that of fresh egg yolk. Further, Debolt (1982) reported differences in nutritional and sensory qualities of spray-dried egg yolk as compared to fresh egg yolk for the mirid *Lygus hesperus* Knight (Hemiptera: Miridae). Nonetheless, reproductive rates of *A. swirskii* on the powdered diets in the present study were comparable to the values found by Nguyen et al. (2013) on the dried fruit mite *C. lactis* and higher than the values reported earlier on some of the predator's natural prey (Wimmer et al. 2008; Ragusa and Swirski 1977). Additionally, the powdered diets proved to be more structurally stable than the freeze dried diets, which may enhance their practical value in rearing systems and as supplemental foods in the crop.

Cattail (*T. latifolia*) pollen has become a standard food in many laboratory studies on phytoseiids because it is a nutritionally optimal food source for the mites and relatively easy to collect in large quantities (Nomikou et al. 2002; Park et al. 2011). However, biological parameters of a given species on this food may vary depending on the quality of the pollen batch used. We observed a substantial difference in r_m-values (0.158 and 0.210, respectively) between the present study and a previous study (Nguyen et al. 2013), using the same environmental conditions and the same population of *A. swirskii* but a different batch of *T. latifolia* pollen. The quality of a pollen batch is influenced by harvesting time (immature pollen grains may have a lower nutrient content), by weather conditions at the time of pollen harvest (Coates et al. 2006), and by the duration and conditions of storage and shipment (Bogdanov 2004).

In conclusion, *A. swirskii* was capable of handling and feeding on (powdered) solid artificial diets, allowing the mite to develop and reproduce successfully for at least a single generation. Freeze-drying of liquid diets did not influence their acceptability and nutritional quality for the mite. Artificial diets entirely composed of powdered/dry ingredients were somewhat inferior to lyophilized liquid diets in terms of their nutritional value, but did support development and reproduction of the phytoseiid and were physically more stable in the rearing environment than the lyophilized diets. These findings indicate the potential of dry artificial diets for use in part of the production cycle of *A. swirskii* or as supplemental foods to sustain its populations in the crop after release. Arguably, more studies are needed to assess the practical applicability of artificial diets in support of biological control programmes using phytoseiid mites. First, it is warranted to assess the value of the presented artificial diets for supporting the population growth of other generalist predatory mites. The effects of long-term rearing of the mites on artificial diets on their quality as biological control agents also need to be explored. Further, field research is needed to evaluate the suitability of the tested diets in the crop environment, with regard to their practical value to support populations of *A. swirskii* or of other predatory mites, and possible undesired effects of their application on populations of arthropod pests (like omnivorous thrips who may also be able to use the diets) and on the physiology and quality of the crop plants. For instance, the powdered diets are included in an ongoing greenhouse study to support the pre-establishment of *A. swirskii* for improving thrips control in chrysanthemum.

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