Original Research Article: full paper

(2023), «EUREKA: Life Sciences»
Number 1

ABUNDANCE, FORAGING BEHAVIOR AND POLLINATION EFFICIENCY OF INSECTS VISITING THE FLOWERS OF AONLA (EMBLICA OFFICINALIS)

Reena Saini
Laboratory of Animal Behavior & Simulated Ecology
Department of Zoology[1]

Ram Chander Sihag✉
Laboratory of Animal Behaviour & Simulated Ecology
Department of Zoology[1]
rcsihag@hau.ac.in

[1]*College of Basic Sciences & Humanities*
CCS Haryana Agricultural University
Main rd, Azad Nagar, Hisar, Haryana, India, 125004

✉**Corresponding author**

Abstract

Many insect species visit the flowers of a plant and play an important role in their pollination. Of late, the interest of the pollination biologists has been to determine their relative contribution towards the reproductive success of the plant. Such information is lacking on the pollinators of Aonla (*Emblica officinalis* Gaertn.), a plant of very high nutritive and medicinal importance. Therefore, let's attempt to make this study to generate such information on this plant. The study was conducted on three varieties of Aonla (viz. Chakaiya, NA-7 and NA-10) for two years. An entire range of flower visitors of this fruit plant was captured with hand net from its field during its flowering period and were identified. On the basis of foraging mode, the flower visitors were characterized as pollinators and non-pollinators. Their abundances, foraging rates, activity durations and number of pollen grains carried on the surface were recorded, and these parameters were used to determine their relative contribution towards the reproductive success of this plant. Among the 12 insect species visiting the flowers of Aonla at the study site, 5 belonged to Hymenoptera, 6 to Diptera and one to Lepidoptera. *Apis dorsata* was the most abundant visitor having maximal foraging rate and carried maximal number of loose pollen grains, followed by *A. mellifera*, *A. florea* and *Sarcophaga* sp; other visitors had lesser values of these parameters. On the basis of these parameters, melittophilous mode of pollination was found to predominate in Aonla. However, the plant was found to be benefitted from the multispecies pollinator guild, and the pollinator diversity seemed to matter for maximization of pollination in Aonla. Therefore, there is a dire need to conserve the pollinator diversity.

Keywords: Aonla, *Emblica officinalis,* flower visitors, honey bee, diversity, foraging behavior, pollination efficiency.

DOI: 10.21303/2504-5695.2023.002738

1. Introduction

A wide variety of insets visit the flowers of plants [1]. Some of these are strictly pollinators, some are strictly nectar thieves, some others are both pollinators as well as nectar thieves [2, 3]; some are very fast foragers while others are extremely slow foragers; some are in highly abundant while others are in scanty numbers [3–9]. On the basis of these parameters, if evaluated rationally, all the flower visiting insects are not equally important to the plant [3]. This is because; these visitors do not contribute equally towards the reproductive success of a plant [3]. Some of the visitors are highly efficient in transferring pollen from anthers to the stigma of the flower while others completely fail in doing so or these are less efficient. This pollen transfer efficiency is measured in terms of pollination efficiency of the visitor and this is the measure of contribution of a visitor towards the reproductive success of the plant. Which parameters of the flower visitors determine their pollination efficiency and to which extent is not fully understood?

Many earlier studies could reveal the dependence of cultivated plants on insects for the pollination of their flowers. These plants included; pigeon pea (*Cajanus cajan*) [4], sunflower

(*Helianthus annuus* L) [5], cauliflower (*Brassica oleracea* var. botrytis) [6], coriander (*Corriandrum sativum* L.) [7], carrot (*Daucus carota* L.), fennel (*Foeniculum vulgare* L.) and onion (*Allium cepa* L.) [8], sarpagandha (*Rauvolfia serpentina*) [9], the European plum (*Prunus domestica* L.) [10], and also some other oilseed, vegeTable and condiment plants [1, 2]. However, this report is not exhaustive and many such reports are now available [11].

Earlier many methods were used to measure the pollination efficiency of flower visitors. For example: examining the full range of floral visitors in a natural community [4–9, 12–18] and observation of their foraging behavior [4–9, 19]; the degree of pollen removal [3, 20], analysis of identity, placement and quantity of pollen grains on a visitor's body [13, 20, 21], examining the number of pollen grains transported [3, 13, 21, 22], the amount of pollen deposited on stigma [3, 18, 23]; or devising index values by supplementing behavioral data with visitor abundance [4–9, 24]. Some workers have combined behavioral observations of blooms visitors with pollen loads they deposit on receptive stigmas [25–27]; whereas others have designated seed set efficiency as pollination efficiency [12, 15, 16, 28–30]. Some workers have correlated seed set with the number of deposited pollen grains [13, 21, 26, 31, 32], whereas others have correlated this with the number of pollinator visits or their visitation rate [26, 33–35].

Aonla (*Emblica officinalis* Gaertn.) is an important fruit plant of sub-tropical climates. The fruit has high nutritious and medicinal values. Normal fruit is rich in vitamin C, and also contains nicotinic acid, carbohydrates, fiber, iron, protein, minerals, and phosphorus [36–38]. The fruit is used for making pickles and preserves [39] and is an integral ingredient of Chayawanprash and triphala, the very well known Ayurvedic food and medicine [40–42]. Due to its immense nutritive and therapeutic value [42–48], this plant has fascinated the farmers for its cultivation in many parts of Asia [49].

The earlier studies revealed that Aonla produced unisexual and monoecious flowers; male flowers appearing first in the form of cluster at the basal part of determinate shoot followed by the female flowers in the axil of leaves at the distal end of same shoot [50, 51], and the sex ratio in the inflorescences of Aonla was male biased [50, 52]. Due to this sexual heterogeneity, fruit set in this plant is possible only through cross-pollination of its flowers for which a biotic pollen vector is essential. That is why; this plant makes an ideal material for this study. Many insect species visit the flowers of entomophilous plants however their individual importance towards the reproductive success of a plant is not known. We have tried to solve this problem.

2. Materials and Methods

The present study was carried out at the Research Farm of Department of Horticulture and in the Apidology Laboratory of the Department of Zoology and Aquaculture of CCS Haryana Agricultural University, Hisar. Three varieties of Aonla viz. Chakaiya, NA-7 and NA-10, selected for this study, were grown in the adjacent plots [50].

2. 1. Diversity of insect visitors

To determine the spectrum of different insects visiting the blossom of three varieties of Aonla during their flowering period, the insects were collected by hand net with 30 cm ring diameter. Sweeps were made throughout the blooming period in both the years at two hourly intervals from morning to the evening. Any new visitor observed on the flower at any other time of the day was also captured. Insect collections were started one week after the commencement of flowering and continued till the flowering was over [50]. The captured insects were then killed in potassium cyanide bottle and preserved as dry specimens and were got identified from the Taxonomy section of the Department of Entomology, CCS, Haryana Agricultural University, Hisar, and a record of the flower visitors was prepared.

2. 2. Relative contribution of the pollinators towards the pollination of Aonla flowers

2. 2. 1. Abundance of insect visitors

Abundances of different insect visitors/pollinators of Aonla crop mentioned above were studied during its blooming period in 2009 and 2010. Three floral branches of 1 m^2 size each were randomly selected at 6 feet height in each plant area. The total number of different insects visiting these branches was recorded for five minutes at an interval of one and a half hour starting from the commencement to the cessation of their activity during the flowering period of the crop following method of Sihag [1]. The observations were recorded at weekly intervals.

2. 2. 2. Activity duration of the visitors

The activity duration of pollinators was determined by recording their times of commencement and cessation of foraging activity on the crop. Mean activity duration was determined using following formula [4]:

$$T = 1/N\left[\sum_{i=1}^{n}\left(n_i \times t_i\right)\right],$$

where T – mean activity duration of pollinator;

n_i – total number of insect species at i-th hour of the day;

T_i – total foraging activity duration of the visitors of a species active at i-th hour of the day;

n – total number of visitors of a species through the course of the day.

2. 2. 3. Foraging behaviour of the insect visitors

2. 2. 3. 1. Foraging mode

On the basis of foraging modes (method of working by a forager on a flower while harvesting pollen and/or nectar reward) foraging behaviours of the insects visiting the blossoms of Aonla were recorded [2, 3]. Accordingly visitors were categorised as pollinators/non pollinators.

2. 2. 3. 2. Foraging rate

Foraging rates of the insect pollinators was recorded in terms of the number of flowers visited per minute. A total of ten insect pollinators of each species were observed for recording foraging rate. Accordingly, the average number of flowers visited/minute was calculated for each species. The number of flowers visited per minute included the flying time from one flower to another. For this, observations were recorded at one and a half hour interval on a day and were repeated at weekly intervals during the flowering period of the plant and at sunny days between 1000–1200 h.

2. 2. 4. Loose pollen grains sticking to the body of the pollinator

Loose pollen grains sticking to the body of different insect pollinator species were recorded using method Sihag [3]. The foraging insect pollinators on different varieties of Aonla were captured with the help of a forceps to avoid shaking of their body and their hind legs were amputated, and were kept in 70 per cent alcohol in glass vials. They were shaken vigorously to wash out the pollen grains from their bodies. Total volume of the rinsate was made to 5 ml before pollen count. An aliquot, 0.01 ml (replicated 5 times) was taken and with the help of a haemocytometer and binocular microscope (15×10 magnification) the number of pollen grains was counted. Then total number of pollen grains in the whole rinsate was calculated [3]. The observations were replicated five times. Ten individuals of each species were captured for counting of loose pollen grains between 800 and 1000 h of the day, when the insect visitors showed peak foraging activity.

2. 2. 5. Effect of multiple visits of pollinators on the fruit set of Aonla

Under this treatment, the newly opened female flowers of a variety were randomly selected and were allowed to receive the visits of a pollinator species. The one day old female flowers of Aonla were selected [50] and the foragers of a species were allowed to visit the separate flowers for 1 visit, 2 visits and 3 visits. Such flowers were individually enveloped till fruit set. For each treatment, 50 flowers were taken in each variety and each treatment was replicated thrice to record the yield data for each treatment.

2. 6. Pollinating efficiency (Number of pollen transferring visits per minute)

For different pollination parameter viz. population abundance of the flower visitors, their foraging rates and mean activity duration of the flower visitors and loose pollen grains on the body of pollinators, their performance scores (*PS*) were derived for each species using following formula [4]:

$$PS_{ij}=(N_{ij}/N_j)\times S,$$

where PS_{ij} – performance score of the *i*-th species for *j*-th parameter;

N_{ij} – importance value of the *i*-th species for *j*-th parameter;

N_j – total importance values of all species for *j*-th parameter;

i – 1 to x, taking positive, whole number and finite value;

j – 1 to r, taking positive, whole number and finite value;

S – total number of species.

From various performance scores for different attributes of a species, pollinating index (*PI*) of each species was derived by multiplying all the PSs of that species. The PSs so derived were then compared and, on the basis of their values, different species were ranked for their contribution towards the reproductive success (pollinating efficiency) of this plant.

2. 7. Statistical Analysis

All the experiments were laid down in "completely randomised design" following Snedecor and Cochran [53] with two way ANOVA and the means were compared at 5 per cent level of significance.

3. Results

3. 1. Diversity of insects visiting Aonla

In 2009 and 2010, a total of twelve species of insects were observed on the three varieties of Aonla during its blooming period in March- April. Out of these insect visitors, five insect species belonged to the order Hymenoptera, six species belonged to the order Diptera and one to Lepidoptera. The hymenopterous species included *Apis dorsata*, *A. mellifera* and *A. florea* which were from the family Apidae. *Pollistes hebraeus* belonged to the family Vespidae and *Halictus* were from the family Halictidae (**Fig. 1**, **Table 1**).

Table 1

Different insects visiting the flowers of Aonla at Hisar during 2009 and 2010

Sr. No.	Insect Species	Order	Family
1	*Apis dorsata* F.	Hymenoptera	Apidae
2	*Apis mellifera* L.	Hymenoptera	Apidae
3	*Apis florea* F.	Hymenoptera	Apidae
4	*Polistes hebraeus* F.	Hymenoptera	Vespidae
5	*Halictus* sp.	Hymenoptera	Halictidae
6	*Eristalis* sp.	Diptera	Syrphidae
7	*Episyrphus* sp.	Diptera	Syrphidae
8	*Syrphus* sp.	Diptera	Syrphidae
9	*Syritta* sp.	Diptera	Syrphidae
10	*Sarcophaga* sp.	Diptera	Sarcophagidae
11	*Chrysoma bezziana* V.	Diptera	Calliphoridae
12	*Psichotoe duvauceli* (Boisduval)	Lepidoptera	Arctiidae

Among dipterans, *Sarcophaga* sp. belonged to family Sarcophagidae, *Chrysoma bezziana* to the family Calliphoridae and *Eristalinus*, *Episyrphus*, *Syrphus* and *Syritta* belonged to the family

Syrphidae. The lepidopteran species *Psichotoe duvauceli* belonged to the family Arctiidae. The insect visitors were common in 2009 and 2010 to all the three varieties of Aonla.

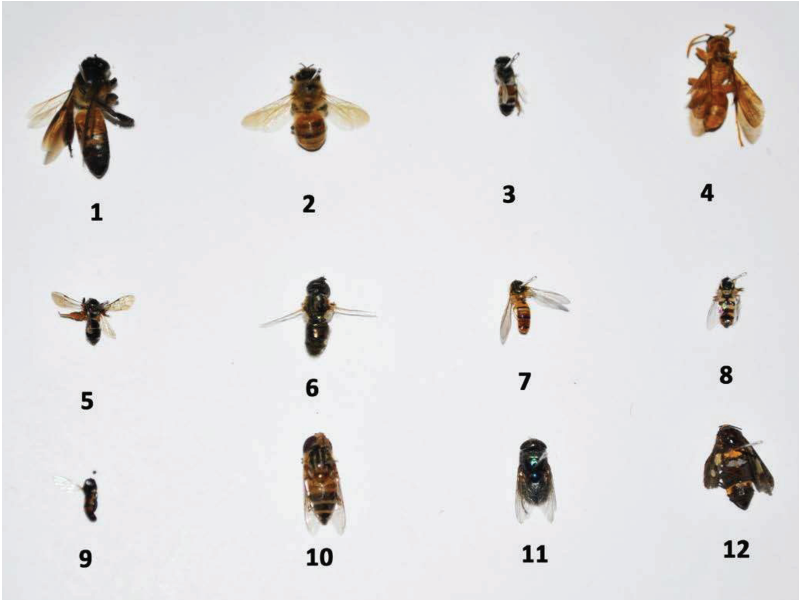

Fig. 1. Different insects visiting the flowers of Aonla in 2009 and 2010 (Nomenclature has been given in **Table 1**)

3. 2. Relative contribution of the pollinators towards the pollination of Aonla flowers

3. 2. 1. Abundance of insect visitors of Aonla

The pattern of average abundance of different insect species visiting Aonla blossoms on the three varieties viz. Chakaiya, NA-7 and NA-10 is presented in **Tables 2, 3** for 2009 and 2010, respectively.

The major insects visiting the Aonla blossoms in all the three varieties in 2009 as well as 2010 included the hymenopterans namely three species of honey bees, *Apis dorsata, A. mellifera* and *A. florea* and a dipteran *Sarcophaga*. The rest of the insect visitors which included a wasp (*Polistes herbraeus*), a bee (*Halictus* sp.), 4 flies (*Eristalis* sp., *Episyrphus* sp., *Syrphus* sp., *Syritta* sp.) and a butterfly (*Psichotoe duvauceli*) were clubbed under "other insect pollinators".

Among the different insect visitors of Aonla blossoms in all the three varieties, only hymenopterans and dipterans were found to be the dominant visitors. The rest were non dominant visitors.

3. 2. 1. 1. Patterns of abundance of insects during 2009

During 2009, the mean abundance of *Apis dorsata* was 8.18 bees/m^2 on NA-7 followed by Chakaiya (7.04 bees/m^2) and NA-10 (6.36 bees/m^2) (**Table 2**). The difference was found to be significant for *A. dorsata* among three varieties ($p \le 0.05$, ANOVA, **Table 2**). Second dominant species *A. mellifera* showed maximum abundance on NA-7 (5.33 bees/m^2) followed by Chakaiya (4.41 bees/m^2) and NA-10 (3.98 bees/m^2). Differences in mean abundance of all varieties were significant ($p \le 0.05$, ANOVA, **Table 2**).

Similar trend was observed in *A. florea* which showed maximal abundance on NA-7 (4.21 bees/m^2) followed by on Chakaiya (3.57 bees/m^2) and NA-10 (3.17 bees/m^2). *Sarcophaga* species exhibited maximal abundance on NA-7 (2.37 insects/m^2) followed by on Chakaiya (2.03 insects/m^2) and NA-10 (1.82 insects/m^2). Other insect pollinators though present in small number showed maximal abundance on NA-7 (1.30 insects/m^2) followed by on Chakaiya (1.01 insects/m^2) and NA-10 (0.84 insects/ m^2). Irrespective of the insect pollinator species, the abundance among three varieties differed significantly ($p \leq 0.05$, ANOVA, **Table 2**) and NA-7 showed maximal abundance (4.28 insects/m^2) followed by on Chakaiya (3.61 insects/m^2) and NA-10 (3.23 insects/m^2).

Table 2

Relative abundance of different insect pollinators on three varieties of Aonla in 2009

Variety	No. of insect visitors (per 5 min/m^2)*					
	Apis dorsata	***A. mellifera***	***A. florea***	***Sarcophaga* sp.**	**Other insect pollinators**	*****Mean±S.E.**
Chakaiya	7.04*±0.72	4.41±0.57	3.57±0.49	2.03±0.33	1.01±0.22	3.61^b±0.32
NA-7	8.18±0.88	5.33±0.72	4.21±0.52	2.37±0.39	1.30±0.25	4.28^a±0.39
NA-10	6.36±0.61	3.98±0.53	3.17±0.42	1.82±0.28	0.84±0.15	3.23^c±0.28
**Mean±S.E.	7.26^a±0.44	4.49^b±0.37	3.65^c±0.28	2.07^d±0.20	1.05^e±0.12	–

Note: – mean±S.E. of 135 observations; ** – mean±S.E. of 405 observations; *** – mean±S.E. of 675 observations; C.D. values (p=0.05) for variety=0.34, for species=0.44. Means with the dissimilar letters differ significantly.*

3. 2. 1. 2. Patterns of abundance during 2010

The mean abundance of *Apis dorsata* was 9.11 bees/m^2 on NA-7 followed by Chakaiya (7.62 bees/m^2) and NA-10 (6.93 bees/m^2) (**Table 3**). The differences were significant among all the three varieties for abundance of *A. dorsata* ($p \leq 0.05$, ANOVA, **Table 3**).

Table 3

Relative abundance of different insect pollinators on three varieties of Aonla in 2010

Variety	No. of insect visitors (per 5 min/m^2)*					
	Apis dorsata	***A. mellifera***	***A. florea***	***Sarcophaga* sp.**	**Other insect pollinators**	*****Mean±S.E.**
Chakaiya	7.62±0.72	4.79±0.60	3.95±0.49	2.36±0.36	1.13±0.23	3.97^b±0.33
NA-7	9.11±0.92	5.77±0.76	4.60±0.50	2.69±0.38	1.44±0.26	4.72^a±0.40
NA-10	6.93±0.68	4.53±0.56	3.54±0.44	2.02±0.32	1.04±0.17	3.61^c±0.30
**Mean±S.E.	7.89^a±0.46	5.03^b±0.38	4.03^c±0.27	2.36^d±0.21	1.20^e±0.13	–

Note: – mean±S.E. of 135 observations; ** – mean±S.E. of 405 observations; *** – mean±S.E. of 675 observations; C.D. values (p=0.05) for variety=0.34, for species=0.44. Means with the dissimilar letters differ significantly.*

The abundance of *A. mellifera* was 5.77 bees/m^2 on NA-7 followed by on Chakaiya (4.79 bees/m^2) and NA-10 (4.53 bees/m^2). The differences were significant between the three varieties ($p \leq 0.05$, ANOVA, **Table 3**). The third abundant insect pollinator species was *A. florea* and its abundance followed the similar trend with maximal number on NA-7 (4.60 bees/m^2) followed by on Chakaiya (3.95 bees/m^2) and NA-10 (3.54 bees/m^2). All the three varieties differed significantly.

The abundance of *Sarcophaga* was maximum on NA-7 (2.69 insects/m^2) followed by on Chakaiya (2.36 insects/m^2) and NA-10 (2.02 insects/m^2). The differences were significant among all varieties ($p \leq 0.05$, ANOVA, **Table 3**).

The abundance of other insect pollinators on NA-7 was 1.44 insects/m^2 followed by on Chakaiya (1.13 insects/m^2) and NA-10 (1.04 insects/m^2). Irrespective of insect pollinator species all three varieties differed significantly for abundance of different insect pollinators ($p \leq 0.05$, ANOVA, **Table 3**). NA-7 showed maximal abundance (4.72 insects/m^2) followed by Chakaiya (3.97 insects/m^2) and NA-10 (3.61 insects/m^2).

The abundance data clearly revealed that honey bees constituted more than 85 percent of the flower visitors of Aonla whereas other visitors comprised only about 16 percent of the total. Thus pollination in Aonla seemed to be predominantly brought by the honey bees.

3. 2. 1. 3. Relative preference for male and female flowers

The visitors of Aonla blossoms foraged both on male and female flowers indiscriminately and made preferably more number of visits on male flowers. On male flowers, the bees made 76 %

of their total visits, *Sarcophaga* made 57 % and rest of the insect pollinators made 62 % of their total visits in all the three varieties of Aonla (**Fig. 2**).

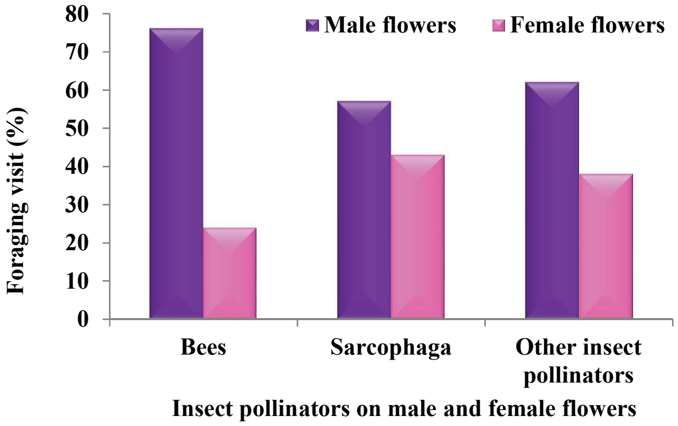

Fig. 2. Relative preferences of different visitors of male and female flowers of Aonla

3. 3. Foraging behaviour of insect visitors of Aonla flowers

3. 3. 1. Foraging modes of insect visitors of Aonla flowers

The insect visitors of Aonla flowers visited the crop mainly for pollen collection as it was a good source of pollen but poor source of nectar. The copious anthers bearing pollen on the Aonla flowers were easily accessible to the insects visiting the Aonla blossoms thus serving as the pollinators of the Aonla flowers. The major pollinators were *Apis dorsata, A. mellifera, A. florea, Sarcophaga* sp. and other insect pollinators from diptera and hymenoptera. All of these pollinators approached the flowers from their front (**Fig. 3–8**). The honey bee species *A. dorsata, A. mellifera* and *A. florea* foraged for nectar and pollen on the Aonla crop and deliberately collected the pollen by scrubbing their legs on the dehisced anthers due to which their bodies got heavily dusted with pollen. There was sternotribic mode of pollen transfer. While working on the flowers, the pubescent hairs present on the ventral side of the bodies and legs of bees got dusted with pollen. The bees thus disseminated pollen from the anthers of male flowers to the stigmas of female flowers and acted as the important pollinators of the Aonla blossoms. The dipterous flies were attracted to the flower mainly for nectar, which was scanty in Aonla flower and served as involuntarily pollinators by the inadvertently transfer of pollen grains from the anthers to the stigmas while attempting to collect nectar (**Fig. 3–8**).

Fig. 3. *Apis dorsata* visiting the flowers of Aonla

Fig. 4. *Apis mellifera* visiting the flowers of Aonla

Fig. 5. *Apis florea* visiting the flowers of Aonla

Fig. 6. *Pollisteshebraeus* visiting the flowers of Aonla

Fig. 7. *Sarcophaga* sp. visiting the flowers of Aonla

Fig. 8. *Syrphus* sp. visiting the flowers of Aonla

3. 3. 2. Foraging rates of insect visitors to Aonla flowers

Foraging rates of insect foragers differed significantly among the visitor species in all the three varieties of Aonla viz. Chakaiya, NA-7 and NA-10 in 2009 as well as 2010 ($p \leq 0.05$, ANOVA, **Tables 4, 5**).

Table 4

Foraging rates of insect pollinators of three varieties of Aonla in 2009

Variety	No. of flowers visited per minute*					
	Apis dorsata	*A. mellifera*	*A. florea*	*Sarcophaga* sp.	Other insect pollinators	***Mean±S.E.
Chakaiya	11.27±0.57	6.97±0.55	5.64±0.45	2.76±0.54	1.22±0.19	5.57^{b}±0.46
NA-7	12.08±0.59	7.84 ±0.57	6.66±0.48	3.38±0.56	1.42±0.22	6.27^{a}±0.48
NA-10	10.78±0.56	6.64±0.53	5.21±0.44	2.63±0.51	1.07±0.18	5.27^{c}±0.44
**Mean±S.E.	11.38^{a}±0.57	7.15^{b}±0.55	5.84^{c}±0.46	2.92^{d}±0.53	1.23^{e}±0.19	–

Note: – mean±S.E. of 10 observations; ** – mean±S.E. of 50 observations; *** – mean±S.E. of 90 observations; C.D. values (p=0.05) for species=0.256, for variety=0.198. Means with the dissimilar letters differ significantly.*

In 2009, foraging rate on the variety Chakaiya was 11.27 flowers/minute of *Apis dorsata,* 6.97 flowers/minute of *A. mellifera,* 5.64 flowers/minute of *A. florea,* 2.76 flowers/minute of *Sarcophaga* and 1.22 flowers/minute of other insect pollinators; the respective values of these pollinators on NA-7 were 12.08, 7.84, 6.66, 3.38 and 1.42 flowers/minute; and on NA-10 were 10.78, 6.64, 5.21, 2.63 and 1.07 flowers/minute (**Table 4**). Out of all species, foraging rates of *Apis dorsata* were maximum on all the three varieties; the differences were significant ($p \leq 0.05$, ANOVA, **Table 4**).

Table 5

Foraging rates of insect pollinators of three varieties of Aonla in 2010

Variety	No. of flowers visited per minute*					
	Apis dorsata	***A. mellifera***	***A. florea***	***Sarcophaga* sp.**	**Other insect pollinators**	*****Mean±S.E.**
Chakaiya	11.60±0.53	7.29±0.57	5.93±0.46	3.09±0.55	1.39±0.20	5.86^{b}±0.46
NA-7	12.33±0.56	8.18±0.55	6.91±0.53	3.58±0.56	1.54±0.23	6.51^{a}±0.48
NA-10	11.07±0.56	6.90±0.57	5.47±0.43	2.82±0.52	1.22±0.18	5.50^{c}±0.45
**Mean±S.E.	$11,67^{a}$±0.46	7.46^{b}±0.38	6.10^{c}±0.27	3.16^{d}±0.21	1.38^{e}±0.13	–

Note: – mean±S.E. of 10 observations; ** – mean±S.E. of 50 observations; *** – mean±S.E. of 90 observations; C.D. values (p=0.05) for species=0.30, for variety=0.23. Means with the dissimilar letters differ significantly.*

In 2010, foraging rate on the variety Chakaiya was 11.60 flowers/minute of *Apis dorsata,* 7.29 flowers/minute of *A. mellifera,* 5.93 flowers/minute of *A. florea,* 3.09 flowers/minute of *Sarcophaga* and 1.39 flowers/minute of other insect pollinators; the foraging rates of respective pollinators on NA-7 were 12.33, 8.18, 6.91, 3.58 and 1.54 flowers/minute; and on NA-10 were 11.07, 6.90, 5.47, 2.82 and 1.22 flowers/minute.

As is clearly evident, on all the three varieties, foraging rates of *A. dorsata* were maximal followed by *A. mellifera, A. florea, Sarcophaga* and other insect pollinators and the differences were significant ($p \leq 0.05$, ANOVA, **Table 5**). On this basis too, honey bees seemed to be the better pollinator of Aonla flowers than other insects.

3. 4. Activity duration of the insect pollinators of Aonla flowers

Out of the insect pollinators visiting the Aonla blossoms, the honey bee *Apis dorsata,* was found active at 0630 h and remained active for the whole period of observation, i.e. up to 1830 h. *A. mellifera* and *A. florea* commenced their activity at 0800 h and remained active till 1700 h. *Sarcophaga,* on the other hand started a bit late at 0930 h and the dipterans commenced their activity at 1100 h. These insect species remained active till 1530 h. The mean foraging activity duration differed among different species, being highest of *A. dorsata* on all the three varieties in both the years followed by *A. florea, A. mellifera and Sarcophaga*. The other insect pollinators which included some dipterans and hymenopterans were the least active of all. Among all the insect pollinators, *A. dorsata* remained active for longest duration on NA-7 (5.39 and h) in 2009 and 2010 respectively, followed by Chakaiya (5.22 and 5.36 h) and NA-10 (5.20 and h) in 2009 and 2010, respectively (**Tables 6, 7**). The mean activity duration for *A. mellifera, A. florea, Sarcophaga* and other insect pollinators was 4.05, 4.07, 2.93 and 2.33 h on Chakaiya; 4.13, 4.10, 2.86 and 2.31 h on NA-7 and 4.01, 3.93, 2.82 and 2.19 h on NA-10 in 2009 (**Table 6**). The mean activity duration in 2010 was similar to 2009 with *A. dorsata* at the top. For *A. mellifera, A. florea, Sarcophaga* and other insect pollinators, the mean activity duration was 4.03, 4.13, 2.84 and 2.35 h on Chakaiya; 4.13, 4.10, 2.88, 2.40 and 3.80 h on NA-7 and 4.09, 4.00, 2.89 and 2.26 h on NA-10 (**Table 7**). Irrespective of the insect pollinator species, all the insect pollinators remained active for longest duration on NA-7 (3.76 and 3.80 h) followed by Chakaiya (3.72 and 3.74 h) and NA-10 (3.63 and 3.71 h) in 2009 and 2010, respectively (**Tables 6, 7**).

Table 6

Mean activity duration of the insect visitors of Aonla in 2009

Insect Pollinators	Mean activity duration (h) on the varieties of Aonla		
	Chakaiya	NA-7	NA-10
Apis dorsata	5.22	5.39	5.20
A. mellifera	4.05	4.13	4.01
A. florea	4.07	4.10	3.93
Sarcophaga sp.	2.93	2.86	2.82
Other insect pollinators	2.33	2.31	2.19
Mean	3.72	3.76	3.63

Table 7

Mean activity duration of the insect visitors of Aonla in 2010

Insect Pollinators	Activity duration (h) on the varieties of Aonla		
	Chakaiya	NA-7	NA-10
Apis dorsata	5.36	5.47	5.32
A. mellifera	4.03	4.13	4.09
A. florea	4.13	4.10	4.00
Sarcophaga sp.	2.84	2.88	2.89
Other insect pollinators	2.35	2.40	2.26
Mean	3.74	3.80	3.71

3. 5. Number of loose pollen grains on the body of pollinators

In 2009, irrespective of variety, average number of loose pollen grains was maximum (6538.80) on body of *Apis dorsata* followed by *A. mellifera* (4608.03), *A. florea* (4320.20), *Sarcophaga* (3247.63) and other insect pollinators (737.13). The differences were found to be significant among the number of loose pollen grains on the body of various pollinators (p=0.05, ANOVA, **Table 8**).

Table 8

Number of loose pollen grains carried by the insect pollinators of three varieties of Aonla during 2009

Insect pollinators	Number of loose pollen grains*			
	Chakaiya	NA-7	NA-10	Mean±S.E.
Apis dorsata	6616.70±173.82	6878.00±182.57	6121.70±166.46	6538.80^{a}±113.37
A. mellifera	4569.70±199.15	4800.80±213.97	4453.60±196.63	4608.03^{b}±116.51
A. florea	4205.10±188.40	4595.00±197.56	4160.50±169.88	4320.20^{c}±109.66
Sarcophaga sp.	3267.00±162.41	3382.60±159.62	3093.30±152.37	3247.63^{d}±90.91
Other insect pollinators	710.10±101.09	928.90±116.71	572.40±100.79	737.13^{e}±65.32
Mean±S.E.	3873.72^{b}±284.11	4117.06^{a}±288.85	3680.30^{b}±270.70	–

*Note: * – each observation is a mean of 10 replications. C.D. (p=0.05) for species=272.82, for varieties=211.32. Means with dissimilar letters differ significantly.*

Similarly in 2010, average number of loose pollen grains was maximum (6590.76) on body of *A. dorsata* followed by *A. mellifera* (4683.03), *A. florea* (4285.16), *Sarcophaga* (3342.87) and the least number was found on the body of other insect pollinators (760.26). The differences were significant among the number of loose pollen grains on the body of all insect species ($p \leq 0.05$, ANOVA, **Table 9**).

Among the three varieties, the number of loose pollen grains carried by different species in both the years were found to be maximal on NA-7 followed by on Chakaiya and minimal on NA-10. The number of loose pollen grains was significantly higher ($p \leq 0.05$, ANOVA, **Tables 8, 9**) on NA-7 than Chakaiya and NA-10 in both the years.

Table 9

Number of loose pollen grains carried by the insect pollinators of three varieties of Aonla during 2010

Insect pollinators	Number of loose pollen grains*			
	Chakaiya	NA-7	NA-10	Mean±S.E.
Apis dorsata	6631.30±169.04	6908.20±178.52	6232.80±145.60	6590.76^{a}±105.49
A. mellifera	4611.60±210.51	4842.10±257.64	4595.40±200.68	4683.03^{b}±126.79
A. florea	4256.30±209.85	4418.60±197.12	4180.60±185.13	4285.16^{c}±111.66
Sarcophaga sp.	3352.20±145.31	3493.60±131.20	3182.80±152.94	3342.87^{d}±83.37
Other insect pollinators	733.00±102.70	962.40±125.16	585.40±101.83	760.26^{e}± 67.97
Mean±S.E.	3923.08^{b}±284.68	4124.98^{a}±287.72	3755.40^{b}±275.31	–

*Note: * – each observation is a mean of 10 replications; C.D. (p=0.05) for species=279.20, for varieties=216.27. Means with dissimilar letters differ significantly.*

3. 6. Effect of multiple visits of bees on fruit set in Aonla

Data presented in **Table 10** on the effect of multiple visits of different pollinators on fruit set in all the three varieties of Aonla reveal that per cent fruit set among visits was non-significant ($p \le 0.05$, ANOVA, **Table 10**). Irrespective of pollinator species, the fruit set with 1 visit, 2 visits and 3 visits was 90.00, 91.20 and 92.00 per cent for Chakaiya, 90.13, 91.60 and 92.00 per cent for NA-7 and 89.20, 90.13 and 91.47 per cent for NA-10, respectively.

In all the varieties, fruit set was maximum for 3 visits followed by 2 and 1 visit, however, the differences were non-significant (p≤0.05, ANOVA, **Table 10**). Irrespective of variety, fruit set was best with *Apis dorsata* as a pollinator, followed by *A. mellifera*, *A. florea*, *Sarcophaga* and other insect pollinators. Fruit set with *A. dorsata*, *A. mellifera*, *A. florea*, *Sarcophaga* and other insect pollinators were 97.33, 94.67, 95.78, 93.11 and 74.44 per cent in Chakaiya; 97.56, 95.78, 94.44, 92.67 and 75.78 per cent in NA-7 and 96.67, 94.67, 93.56, 92.00 and 74.44 per cent in NA-10, respectively. Between *A. mellifera* and *A. florea,* the difference was non-significant, but among other species, it was significant ($p \le 0.05$, ANOVA, **Table 10**).

Table 10

Effect of multiple visits of different pollinators on fruit set of three varieties of Aonla

S. No.	Pollinators	Fruit set (%) in flowers of Aonla due to multiple visits			Mean±S.E.
		1	2	3	
	Chakaiya				
1	*Apis dorsata*	96.67±0.66	97.33±1.33	98.00±0	97.33^{a}±6.78
2	*A. mellifera*	93.33±1.33	94.67±0.66	96.00±1.33	94.67^{b}±7.00
3	*A. florea*	94.67±1.33	96.00±1.16	96.67±1.76	95.78^{b}±6.65
4	*Sarcophaga* sp.	92.00±0.66	93.33±1.33	94.00±1.16	93.11^{c}±6.87
5	Other insect pollinators	73.33±1.16	74.67±0.66	75.33±0.66	74.44^{d}±6.01
	Mean±S.E.	90.00^{a}±2.71	91.20^{a}±2.23	92.00^{a}±2.78	–
	NA-7				
1	*Apis dorsata*	96.00±1.16	98.00±0	98.67±0.66	97.56^{a}±6.93
2	*A. mellifera*	94.67±0.66	96.67±0.66	96.00±1.16	95.78^{b}±7.71
3	*A. florea*	93.33±1.76	94.67±1.76	95.33±1.33	94.44^{b}±7.84
4	*Sarcophaga* sp.	92.00±0	92.67±0.66	93.33±2.00	92.67^{c}±7.65
5	Other insect pollinators	74.67±2.00	76.00±1.16	76.67±0.66	75.78^{d}±6.33
	Mean±S.E.	90.13^{a}±2.40	91.60^{a}±2.56	92.00^{a}±2.37	–
	NA-10				
1	*Apis dorsata*	95.33±0.66	96.00±1.33	98.67±1.76	96.67^{a}±7.63
2	*A. mellifera*	94.00±0	95.33±1.33	94.67±2.00	94.67^{b}±6.29
3	*A. florea*	92.67±1.33	93.33±1.76	94.67±1.76	93.56^{b}±7.07
4	*Sarcophaga* sp.	90.67±0.66	92.00±0.66	93.33±0.66	92.00^{c}±7.11
5	Other insect pollinators	73.33±1.76	74.00±1.16	76.00±1.76	74.44^{d}±6.85
	Mean±S.E.	89.20^{a}±1.77	90.13^{a}±2.38	91.47^{a}±2.21	–

Note: each set had 50 flowers with 50 numbers of expected fruit set in each replicate; replicated three times. C.D. (p=0.05) for visits=N.S., species=1.365, varieties=N.S. Mean with dissimilar letters differ significantly.

3. 7. Pollinating efficiency (number of pollen transferring visits per minute)

From the different pollination attributes viz. relative abundance of the insect visitors (number of insect visitors/m^2/5min), mean foraging activity duration (h), foraging rates (number of flowers visited/min) and number of loose pollen grains on the body of the pollinators, the performance scores were obtained for 2009 and 2010 for all the five insect visitors (**Tables 11, 12**) and the pollination indices were calculated for the different species on all the varieties. The insects were tentatively ranked for their pollinating efficiency. On the basis of the pollination indices derived, *Apis dorsata* was found to be the most efficient pollinator among all the insect pollinators in all the three varieties viz. Chakaiya, NA-7 and NA-10, in 2009 and 2010 followed by *A. mellifera, A. florea, Sarcophaga* and other insect pollinators.

Table 11

Pollinating efficiency ranking of pollinators of three varieties of Aonla based on indices derived from the performance scores of various pollination attributes during 2009

S. No.	Pollinator	Pollination parameters					
		Abundance	Activity duration	Foraging Rate	Pollen grains	Pollination index and rank	Percent pollination
Chakaiya							
1	*Apis dorsata*	1.95	1.40	2.02	1.71	9.43 (I)	73.9
2	*A. mellifera*	1.22	1.08	1.25	1.18	1.94 (II)	15.2
3	*A. florea*	0.99	1.09	1.01	1.09	1.19 (III)	9.51
4	*Sarcophaga* sp.	0.56	0.79	0.50	0.84	0.19 (IV)	1.49
5	Other insect pollinators	0.28	0.63	0.22	0.18	0.01 (V)	0.08
NA-7							
1	*Apis dorsata*	1.91	1.43	1.92	1.67	8.76 (I)	71.68
2	*A. mellifera*	1.25	1.10	1.25	1.16	1.99 (II)	16.28
3	*A. florea*	0.98	1.09	1.06	1.12	1.27 (III)	10.39
4	*Sarcophaga* sp.	0.55	0.76	0.54	0.82	0.19 (IV)	1.55
5	Other insect pollinators	0.30	0.61	0.23	0.23	0.01 (V)	0.08
NA-10							
1	*Apis dorsata*	1.97	1.43	2.05	1.66	9.59 (I)	73.65
2	*A. mellifera*	1.23	1.10	1.26	1.21	2.06 (II)	15.82
3	*A. florea*	0.98	1.08	0.99	1.13	1.18 (III)	9.06
4	*Sarcophaga* sp.	0.56	0.78	0.50	0.84	0.18 (IV)	1.38
5	Other insect pollinators	0.26	0.60	0.20	0.16	0.01(V)	0.08

Table 12

Pollinating efficiency ranking of pollinators of three varieties of Aonla based on indices derived from the performance scores of various pollination attributes during 2010

S. No.	Pollinator	Pollination parameters					
		Abundance	Activity duration	Foraging Rate	Pollen grains	Pollination index and rank	Percent pollination
1	2	3	4	5	6	7	8
Chakaiya							
1	*Apis dorsata*	1.92	1.43	1.98	1.69	9.19(I)	73.46
2	*A. mellifera*	1.21	1.08	1.24	1.18	1.91(II)	15.27I
3	*A. florea*	0.99	1.10	1.02	1.08	1.20(III)	9.6
4	*Sarcophaga* sp.	0.59	0.76	0.53	0.86	0.20(IV)	1.6
5	Other insect pollinators	0.28	0.63	0.24	0.19	0.01(V)	0.08
NA-7							
1	*Apis dorsata*	1.93	1.44	1.89	1.67	8.77(I)	72.3
2	*A. mellifera*	1.22	1.09	1.26	1.17	1.96(II)	16.16
3	*A. florea*	0.97	1.08	1.06	1.07	1.19(III)	9.81
4	*Sarcophaga* sp.	0.57	0.76	0.55	0.85	0.20(IV)	1.65
5	Other insect pollinators	0.30	0.63	0.24	0.23	0.01(V)	0.08

Continuation of Table 12

1	2	3	4	5	6	7	8
			NA-10				
1	*Apis dorsata*	1.92	1.43	2.01	1.66	9.16(I)	72.47
2	*A. mellifera*	1.25	1.10	1.26	1.22	2.11(II)	16.69
3	*A. florea*	0.98	1.08	1.00	1.11	1.17(III)	9.26
4	*Sarcophaga* sp.	0.56	0.78	0.51	0.84	0.19(IV)	1.5
5	Other insect pollinators	0.29	0.61	0.22	0.16	0.01(V)	0.08

From the account on pollination efficiency it is evident that in Chakaiya, in 2009, about 98.44 percent pollination in Aonla was brought by the honey bees and only about 1.56 percent by other pollinators. Same trend was followed by other varieties and in 2010 too. That means, Aonla is predominantly dependent on honey bees for the pollination of its flowers in the semi-arid environment of Northwest India. *A.dorsata* alone brought about 72–73 percent pollination, *A.mellifera* about 14–15 percent, *A. florea* about 9–10 percent, *Sarcophaga* about 1.5 percent and other insects about 0.1 percent.

4. Discussion

In 2009 and 2010, a total of twelve species of insects were observed on the three varieties of Aonla during its blooming period in March- April. The insect visitors were common in 2009 and 2010 to all the three varieties of Aonla (**Table 1, Fig. 1**). Among the different insect visitors recorded, only the hymenopterous species namely *A. dorsata, A. mellifera* and *A. florea* and a dipterous species *Sarcophaga* were the dominant visitors (**Tables 2, 3**). The rest of the insect visitors which included wasp (*Polistes herbraeus*), bee (*Halictus* sp.), flies (*Eristalis* sp., *Episyrphus* sp., *Syrphus* sp., *Syritta* sp.) and a butterfly (*Psichotoe duvauceli*) were the non-dominant visitors and were clubbed under "other insect pollinators." Similar pattern of insect diversity was observed in the earlier studies carried out in the semi-arid environment of Northwest India [4–10].

Maximal abundance of flower visitors was recorded on NA-7, followed by on Chakaiya and NA-10 in both 2009 and 2010. During 2009 and 2010, irrespective of the variety, the abundance of *A. dorsata* was maximal followed by *A. mellifera, A. florea, Sarcophaga* sp. and other insect pollinators. The honey bees were the predominant visitors of the flowers of Aonla in the semi-arid environment of Northwest India. These results resemble the results of other studies carried out in this region [4–10]. The pollinators made preferably more visits on male flowers than female flowers (**Fig. 2**). This may be due to the availability of plenty of pollen in the flowers of this plant. Based on the foraging modes, *A. dorsata, A. mellifera, A. florea, Sarcophaga* sp. were the major pollinators and other insect pollinators which included a few dipterans and hymenopterans were the minor pollinators. All these visitors followed sternotribic mode of pollen transfer. On each variety, in 2009 and 2010, foraging rate of *A. dorsata* was maximal, followed by *A. mellifera, A. florea, Sarcophaga* sp. and other insect pollinators (**Tables 4, 5**).

In the present study, broadly similar pattern of pollinating efficiency of the pollinators was derived by two methods i.e.:

1) on the basis of different pollination parameters (viz. population abundance of flower visitors, activity duration, foraging rates and the number of loose pollen grains on the body of all pollinators);

2) on the basis of percent fruit set due to multiple visits. Pollinating indices clearly indicated that among the insect pollinators, *A. dorsata* came out to be the most efficient pollinator of Aonla in both the years followed by *A. mellifera, A. florea, Sarcophaga* sp. and other insect pollinators (**Tables 11, 12**).

On the basis of multiple visits of pollinators, irrespective of the variety, fruit set (per cent) was best with *A. dorsata* as pollinator of Aonla followed by *A. mellifera, A. florea, Sarcophaga* sp. and other insect pollinators (**Table 10**). The most striking feature of this study is the predominant dependence of Aonla on the honey bees for the pollination of its flowers as more than 98 percent pollination in this fruit plant is brought by the honey bees (three species). However, single species pollination does not seem to be perfect (i.e. 100 percent). *A. dorsata* alone brought about 72–73 percent pollination, *A. mellifera* about 14–15 percent, *A. florea* about 9–10 percent, *Sarcophaga* about 1.5 percent and other insects about 0.1 percent. Therefore, for the realization of maximum pollination (i.e. 100 percent), the Aonla plant has to depends on a multispecies guild of pollinators. This would indicate that pollinator diversity does matter in the pollination of Aonla.

Present study has some limitations. Performance scores derived from the various parameters provide an approximate pattern of measure of pollination efficiency of the pollinators. For determining the actual relative contributions of the pollinators towards the reproductive success of the plant, the behavioral data would need to be supported by the yield data of the visited plant. Therefore, future research should concentrate on the contribution of the pollinator towards the yield performance of the visited plant.

5. Conclusions

Aonla bears unisexual flowers hence pollination of its flowers can be accomplished by a pollen vector. Honey bees were found to be the most abundant and most efficient pollinators of this fruit plant. On the basis of various pollinator parameters and the reproductive success of the plant, melittophilous mode of pollination was found to predominate in Aonla (*Emblica officinalis*) plant in the semi-arid environment of Northwest India. However, the plant did benefit from the multi-species pollinator guild, and the pollinator diversity seemed to seemed to matter in the pollination of Aonla, the plant chosen for this study. Therefore, along with honey bees, conservation of other pollinators is also important. Studies on more plants would be helpful in strengthening the claims of this study.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

This study was carried out under the project ‘B (IV) Plan Agri.’ funded by the State Government of Haryana. RS received University Fellowship during the course of this study.

Data availability

Manuscript has no associated data.

Acknowledgements

Authors are thankful to the Head, Department of Horticulture for providing the field facility and the Head, Department of Zoology for providing laboratory and other facilities. Nidhi Wadhwa provided field assistant in recording of data, Ram Niwas Sheokand and Jay Sihag helped in analysis and tabulation of data.

References

[1] Sihag, R. C. (1986). Insect Pollination Increases Seed Production in Cruciferous and Umbelliferous Crops. Journal of Apicultural Research, 25(2), 121–126. doi: https://doi.org/10.1080/00218839.1986.11100704

[2] Sihag, R. C. (1988). Characterization of the Pollinators of Cultivated Cruciferous and Leguminous Crops of Sub-Tropical Hissar, India. Bee World, 69 (4), 153–158. doi: https://doi.org/10.1080/0005772x.1988.11098972

[3] Sihag, R. C. (2018). Some Unresolved Issues of Measuring the Efficiency of Pollinators: Experimentally Testing and Assessing the Predictive Power of Different Methods. International Journal of Ecology, 2018, 1–13. doi: https://doi.org/10.1155/2018/3904973

[4] Sihag, R. C., Rathi, A. (1994). Diversity, abundance, foraging behaviour and pollinating efficiency of different bees visiting pigeon pea (*Cajanus cajan* (L) Millsp.) blossoms. Indian Bee Journal, 56, 187–201.

[5] Arya, D. R., Sihag, R. C., Yadav, P. R. (1994). Diversity, abundance and foraging activity of insect pollinators of sunflower (*Helianthus annuus* L.) at Hisar (India). Indian Bee Journal, 56, 172–178.

[6] Priti, Sihag, R. C. (1997). Diversity, visitation frequency, foraging behaviour and pollinating efficiency of insect pollinators visiting cauliflower (*Brassica oleracea* L. var botrytis cv. Hazipur Local) blossoms. Indian Bee Journal, 59 (4), 230–237.
[7] Priti, Sihag, R. C. (1999). Diversity, visitation frequency, foraging behaviour and pollinating efficiency of different insect pollinators visiting coriander (*Coriandrum sativum*. .L.) blossoms. Asian Bee Journal, 1 (II), 36–42.
[8] Chaudhary, N., Sihag, R.C., Pandey, M.C. (2009). Relative abundance, diversity and dominance concentration of two honey-bee species on three concurrently flowering crops, onion (*Allium cepa* L.), carrot (*Daucus carota* L.) and fennel (*Foeniculum vulgare* L.). Pestology, XXXIII (7), 9–13.
[9] Wadhwa, N., Sihag, R. C. (2012). Psychophilous Mode of Pollination Predominates in Sarpagandha (*Rauvolfia serpentina*). Journal of Entomology, 9 (4), 187–207. doi: https://doi.org/10.3923/je.2012.187.207
[10] Wadhwa, N., Sihag, R. C. (2015). Melittophilous Mode of Pollination Predominates in European Plum (*Prunus domestica* L.) in the Semi-Arid Environment of Northwest India. Asian Journal of Agricultural Research, 9 (5), 189–207. doi: https://doi.org/10.3923/ajar.2015.189.207
[11] Free, J.B. (1993). Insect pollination of Crops. London: Academic Press.
[12] Schemske, D. W., Horvitz, C. C. (1984). Variation Among Floral Visitors in Pollination Ability: A Precondition for Mutualism Specialization. Science, 225 (4661), 519–521. doi: https://doi.org/10.1126/science.225.4661.519
[13] Primack, R. B., Silander, J. A. (1975). Measuring the relative importance of different pollinators to plants. Nature, 255 (5504), 143–144. doi: https://doi.org/10.1038/255143a0
[14] Bertin, R. I. (1982). Floral biology, hummingbird pollination and fruit production of trumpet creeper (Campsis radicans, Bignoniaceae). American Journal of Botany, 69 (1), 122–134. doi: https://doi.org/10.1002/j.1537-2197.1982.tb13241.x
[15] Motten, A. F. (1983). Reproduction of Erythronium umbilicatum (Liliaceae): pollination success and pollinator effectiveness. Oecologia, 59 (2-3), 351–359. doi: https://doi.org/10.1007/bf00378861
[16] Motten, A. F., Campbell, D. R., Alexander, D. E., Miller, H. L. (1981). Pollination Effectiveness of Specialist and Generalist Visitors to a North Carolina Population of Claytonia Virginica. Ecology, 62 (5), 1278–1287. doi: https://doi.org/10.2307/1937292
[17] Galen, C., Newport, M. E. A. (1987). Bumble bee behavior and selection on flower size in the sky pilot, Polemonium viscosum. Oecologia, 74 (1), 20–23. doi: https://doi.org/10.1007/bf00377340
[18] Herrera, C. M. (1989). Pollinator abundance, morphology, and flower visitation rate: analysis of the “quantity” component in a plant-pollinator system. Oecologia, 80 (2), 241–248. doi: https://doi.org/10.1007/bf00380158
[19] Macior, L. W. (1967). Pollen-foraging behavior of Bombus in relation to pollination of nototribic flowers. American Journal of Botany, 54 (3), 359–364. doi: https://doi.org/10.1002/j.1537-2197.1967.tb06930.x
[20] Conner, J. K., Davis, R., Rush, S. (1995). The effect of wild radish floral morphology on pollination efficiency by four taxa of pollinators. Oecologia, 104 (2), 234–245. doi: https://doi.org/10.1007/bf00328588
[21] Mayfield, M. M., Waser, N. M., Price, M. V. (2001). Exploring the `most effective pollinator principle’ with complex flowers: bumblebees and *Ipomopsis aggregata*. Annals of Botany, 88, 591–596. doi: https://doi.org/10.1006/anbo.2001.1500
[22] Ivey, C. T., Martinez, P., Wyatt, R. (2003). Variation in pollinator effectiveness in swamp milkweed, Asclepias incarnata (Apocynaceae). American Journal of Botany, 90 (2), 214–225. doi: https://doi.org/10.3732/ajb.90.2.214
[23] Muchhala, N., Potts, M. D. (2007). Character displacement among bat-pollinated flowers of the genus Burmeistera: Analysis of mechanism, process and pattern. Proceedings of the Royal Society of London, B, Biological Sciences, 274, 2731–2737. doi: https://doi.org/10.1098/rspb.2007.0670
[24] Ehrenfeld, J. G. (1979). Pollination of Three Species of Euphorbia Subgenus Chamaesyce, with Special Reference to Bees. American Midland Naturalist, 101 (1), 87–98. doi: https://doi.org/10.2307/2424904
[25] Ornduff, R. (1975). Complementary Roles of Halictids and Syrphids in the Pollination of Jepsonia heterandra (Saxifragaceae). Evolution, 29 (2), 371–373. doi: https://doi.org/10.2307/2407227
[26] Sahli, H. F., Conner, J. K. (2007). Visitation, effectiveness, and efficiency of 15 genera of visitors to wild radish, *Raphanus raphanistrum* (Brassicaceae). American Journal of Botany, 94 (2), 203–209. doi: https://doi.org/10.3732/ajb.94.2.203
[27] Meerabai, G. (2012). Visitation rate, effectiveness and efficiency of pollinators to *Cadaba fruiticosa* (Linn) Druce. The Bioscan, 7 (3), 483–485.
[28] Spears, E. E. (1983). A direct measure of pollinator effectiveness. Oecologia, 57 (1-2), 196–199. doi: https://doi.org/10.1007/bf00379581
[29] Morse, D. H., Fritz, R. S. (1983). Contributions of diurnal and nocturnal insects to the pollination of common milkweed (Asclepias syriaca L.) in a pollen-limited system. Oecologia, 60 (2), 190–197. doi: https://doi.org/10.1007/bf00379521
[30] Sampson, B. J., Cane, J. H. (2000). Pollination Efficiencies of Three Bee (Hymenoptera: Apoidea) Species Visiting Rabbiteye Blueberry. Journal of Economic Entomology, 93 (6), 1726–1731. doi: https://doi.org/10.1603/0022-0493-93.6.1726

[31] Kudo, G., Hirao, A. S., Kawai, Y. (2011). Pollination Efficiency of Bumblebee Queens and Workers in the Alpine Shrub Rhododendron aureum. International Journal of Plant Sciences, 172 (1), 70–77. doi: https://doi.org/10.1086/657282

[32] Silander, J. A., Primack, R. B. (1978). Pollination Intensity and Seed Set in the Evening Primrose (Oenothera fruticosa). American Midland Naturalist, 100 (1), 213–216. https://doi.org/10.2307/2424791

[33] Adlerz, W. C. (1966). Honey Bee Visit Numbers and Watermelon Pollination1. Journal of Economic Entomology, 59 (1), 28–30. doi: https://doi.org/10.1093/jee/59.1.28

[34] Schemske, D. W. (1977). Flowering Phenology and Seed Set in *Claytonia virginica* (Portulacaceae). Bulletin of the Torrey Botanical Club, 104 (3), 254–263. doi: https://doi.org/10.2307/2484307

[35] Waser, N. M., Real, L. A. (1979). Effective mutualism between sequentially flowering plant species. Nature, 281 (5733), 670–672. doi: https://doi.org/10.1038/281670a0

[36] Srivastava, R. P. (1964). Chemical composition of fresh and dried Aonla fruits. Science and Culture, 30, 446–447.

[37] Pathak, R. K. (2003). Status report on genetic resources of Indian gooseberry- Aonla (*Emblica officinalis* Gaertn.) in south and south-east Asia. IPGRI Office for south Asia, National Agriculture Science Centre (NASC). New Delhi, 99.

[38] Bajpai, P. N., Shukla, H. S.; Bose, T. K., Mitra, S. K. (Eds.) (2002). Aonla. Fruits: Tropical and Subtropical. Vol. II. Calcutta: Naya Udyog, 523–540.

[39] Arya, A. (2004). Tropical Fruits: Diseases and Pests. Ludhiana: Kalyani Publishers, 256–264.

[40] Kikani, K. P., Sadaria, D. T., Patel, D. R. (2000). Research and development in Aonla. Journal of Medicinal and Aromatic Plant Science, 22 (1), 82.

[41] Rajeshkumar, N. V., Therese, M., Kuttan, R. (2001). Emblica officinalis Fruits Afford Protection Against Experimental Gastric Ulcers in Rats. Pharmaceutical Biology, 39 (5), 375–380. doi: https://doi.org/10.1076/phbi.39.5.375.5902

[42] Nath, V., Kumar, D., Pandey, V. (2008). Aonla. Fruits for the Future: Well Versed Arid and Semi Arid Fruits. Vol. I. Delhi: Satish Serial Publidhing House, 129–163.

[43] Jayaweera, D. M. A. (1981). Medicinal plants (Indigenous and exotic) used in Ceylon. Vol. II. Colombo: The National Science Council of Sri Lanka, 32–33.

[44] Jayshri, S., Jolly, C. I. (1993). Phytochemical, antibacterial and pharmacological investigations on *Monordica charantia* and *Emblica officinalis*. Indian Journal of Pharmacology Science, 1, 6–13.

[45] Rao, T. P., Sakaguchi, N., Juneja, L. R., Wada, E., Yokozawa, T. (2005). Amla (Emblica officinalis Gaertn.) Extracts Reduce Oxidative Stress in Streptozotocin-Induced Diabetic Rats. Journal of Medicinal Food, 8 (3), 362–368. doi: https://doi.org/10.1089/jmf.2005.8.362

[46] Scartezzini, P., Antognoni, F., Raggi, M. A., Poli, F., Sabbioni, C. (2006). Vitamin C content and antioxidant activity of the fruit and of the Ayurvedic preparation of Emblica officinalis Gaertn. Journal of Ethnopharmacology, 104 (1-2), 113–118. doi: https://doi.org/10.1016/j.jep.2005.08.065

[47] Thakur, C. P., Mandal, K. (1984). Effect of *Emblica officinalis* on cholesterol induced atherosclerosis in rabbits. Indian Journal of Medical Research, 79, 142–146.

[48] Yokozawa, T., Young Kim, H., Ju Kim, H., Okubo, T., Chu, D.-C., Raj Juneja, L. (2007). Amla (*Emblica officinalis* Gaertn.) prevents dyslipidaemia and oxidative stress in the ageing process. British Journal of Nutrition, 97 (6), 1187–1195. doi: https://doi.org/10.1017/s0007114507691971

[49] Verma, L. R., Jindal, K. K. (1997). Fruit crops pollination. Ludhiana: Kalyani Publishers, 265–269.

[50] Saini, R., Sihag, R. C. (2019). Flowering Biology and Phenology of Aonla (Emblica officinalis Gaertn.) in the Semi-arid Environment of North-West India. International Journal of Agricultural Research, 15 (1), 1–8. doi: https://doi.org/10.3923/ijar.2020.1.8

[51] Bajpai, P. N. (1968). Studies on flowering and fruit development in Aonla. Horticulture Advances, 7, 38–67.

[52] Dhar, L. (1979). A note on sex expression and bearing behaviour of Banarsi aonla. Progressive Horticulture, 11, 31–33.

[53] Snedecor, G. W., Cochran, W. G. (1967). Statistical Methods. New Delhi: Oxford and IBH Publishing Co. Pvt. Ltd., 593.

Received date 02.12.2022
Accepted date 04.01.2023
Published date 31.01.2023

***How to cite:** Saini, R., Sihag, R. C. (2023). Abundance, foraging behavior and pollination efficiency of insects visiting the flowers of Aonla (Emblica officinalis). EUREKA: Life Sciences, 1, 40–56, doi: http://doi.org/10.21303/2504-5695.2023.002738*