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Pollination Ecology of Rocket (*Eruca vesicaria* (L.) Cav. ssp. *sativa* (Mill.) Thell) in the Semi-Arid Environments of Northwest India: Native Bees Are the Major Pollinators

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Abstract: Several insect species visit the flowers of a plant to obtain floral rewards in the form of pollen and/or nectar. In return, we would anticipate that those visitors would contribute to the reproductive success of the plant. Do these visitors contribute equally towards the reproductive success of the plant? This issue has been the interest of many pollination ecologists. To find a solution to this problem, I investigated the pollination ecology of rocket (*Eruca vesicaria* (L.) Cav. ssp. *sativa* (Mill.) Thell), an important leafy vegetable used as salad. I captured the flower visitors with a hand net from the experimental field and had these identified. I also recorded the number of loose pollen grains carried on the body of the visitors of different species and deposited on the stigmas. Effects of single and multiple visits of visitors on the seed set of rocket flowers were also determined. Abundances and foraging rates of the flower visitors of this species were recorded and their values were used to calculate their respective contributions towards the reproductive success of this species. Five species of Hymenoptera, three of Diptera, one of Lepidoptera, and one of Coleoptera visited the flowers of the rocket. *Apis florea* was the most abundant among the flower visitors, followed by the dipterous flies, *Apis mellifera*, *Apis dorsata*, *Andrena savignyi*, and *Andrena leaena* in descending order. The number of loose pollen grains carried and deposited, foraging behaviors, foraging rates, and abundances did not provide conclusive measures to differentiate the contributions of different flower visitors towards the reproductive success of the rocket. However, the data recorded on abundances, foraging behaviors, and foraging rates together could do so. Accordingly, *Andrena savignyi* was the most efficient pollinator of rocket, followed by *Andrena leaena*, *Apis dorsata*, *Apis mellifera*, and *Apis florea*; dipterous flies were the least efficient pollinators of this plant species. In rocket, 28.84% of pollination was brought by *Andrena savignyi*, 24.69% by *Andrena leaena*, 20.34% by *Apis dorsata*, 18.37% by *Apis mellifera*, and 7.7% by *Apis florea*; dipterous flies caused only 0.06% pollination. Butterflies were very rare and *Coccinella* sp. was not a pollinator of this plant. Therefore, not all the pollinators of rocket contributed equally towards its reproductive success (seed production). Bees brought about 99.94% of total pollination and melittophily distinctly predominated over other pollination modes. However, among the bees, native bees together are the major pollinators in the flowers of rockets and accomplished more than 81.5% pollination. Therefore, the conservation of native bees is most important for the pollination of crops such as rockets.

Keywords: diversity; foraging behavior; pollinator; pollination; pollination efficiency; rocket; *Eruca vesicaria* ssp. *sativa*

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1. Introduction

Pollination is one of the essential ecosystem services as this has a direct influence on the reproductive success of the cross-pollinated plants. A wide variety of animals visit the flowers of a plant to obtain pollen and nectar. In return, the visitors expectedly provide pollination service to the visited flowers. In this process, the pollinators should ensure the reproductive success of the plant [1]. Nevertheless, do all the flower visitors contribute equally towards the reproductive success of a plant they visit? This issue has been the subject of concern and interest of many pollination ecologists.

My earlier studies on the diversity of pollinators revealed that native bees were an integral part of the pollination services in the agroecosystems of northwest India. For example, *Megachile bicolor* F., *Megachile lanata* F., *Xylocopa fenestrata* F., and *Xylocopa pubescens* Spinola were the important pollinators of pigeon pea (*Cajanus cajan* L. Millsp.) [2]; *Megachile nana* Bingham, *Megachile flavipes* Spinola, and *Megachile cephalotes* Smith were the important pollinators of alfalfa (*Medicago sativa* L.) [1,3,4]; *Xylocopa fenestrata* F., *Apis dorsata* F., and *Apis florea* F. were the important pollinators of sunflower (*Helianthus annuus* L.) [5–7]; *Apis dorsata* F. and *Apis florea* F. were the important pollinators of rapeseed (*Brassica campestris* L. var *toria*) [1,5,6], cauliflower (*Brassica oleracea* L. var. *botrytis* cv. Hazipur Local) [5,6,8], onion (*Allium cepa* L.) [5,6,9,10], coriander (*Coriandrum sativum* L.) [5,6,11], fennel (*Foeniculum vulgare* L.) [5,6,10,12], European plum (*Prunus domestica* L.) [5,6,13], and aonla (*Emblica officinalis* Gaertn.) [14]; *Apis florea* F. and *Andrena leaena* Cam. were the important pollinators of carrot (*Daucus carota* L. cv. HC-I) [6,10,15]; and *Xylocopa fenestrata* F., *Xylocopa pubescens* Spinola, *Apis dorsata* F., and *Apis florea* F. were the important pollinators of bath sponge (*Luffa cylendrica* (L.) Roem. [1,5,6], cucumber (*Cucumis sativus* L.) [5,6,16], apple gourd (*Pracitrullus fistulosus* (Stocks) Pangalo [6,17], and wanga (*Cucumis melo* (L.) ssp. *melo*) [6,18]. In all these cases, native bees were the dominant visitors and efficient pollinators of flowers of these crops, and the native bees brought more than 40% of the pollination in these crops.

Many methods were earlier used to measure the contribution of a visitor towards the reproductive success of a plant (in terms of its pollination efficiency). Some researchers examined the full range of floral visitors in a natural community [1,2,7–24] and observed their foraging behavior [1,2,7–18,25]. Others observed the degree of pollen removal [1,26], whereas still others analyzed the identity, placement, and quantity of pollen grains on a visitor's body [1,13,26–28] or the number of pollen grains deposited on the stigma [1,24,29]. Some researchers derived index values from the behavioral data and visitor abundance [1,2,7–18,30], whereas others combined behavioral observations of flower visitors with pollen loads they deposit on stigmas [31–33]. Some workers called seed set efficiency as pollination efficiency [19,21,22,25,34–36], others correlated seed set with the number of deposited pollen grains [19,27,32,37,38], whereas still others correlated this with the number of pollinator visits [31,39–41].

Rocket (*E. vesicaria* ssp. *sativa*), a member of the family Brassicaceae, is an important edible annual plant used as a leaf vegetable for its fresh peppery flavor. This is a self-incompatible plant and, for the pollination of its flowers, pollen must come from another conspecific plant [42]. Insects help increase seed production in this plant through cross-pollination of its flowers [43]. In India, this is a very popular oilseed cash crop grown in the rain-fed areas of the semiarid environment of the northwestern region. Seed production in this crop is pollinator-limited [43]. However, which assemblage of pollinators is associated with the reproductive success (in terms of seed production) of this plant species and their relative contribution is not yet known. The latter knowledge is important for devising the conservation strategies of pollinators in the present context of pollinator declines [5,44]. With this objective, the present study was carried out.

2. Materials and Methods

The rocket (*Eruca vesicaria* (L.) Cav. ssp. *sativa* (Mill.) Thell) crop was grown following general agronomical practices (Figures 1 and 2) at the Oilseeds Research Farm of CCS Haryana Agricultural University, Hisar (India). This place is adjacent to the Thar desert and its agro-climatic conditions have already been described [5,45,46]. All data on abundances and foraging behavior were recorded in the field, whereas data on pollen counts were recorded in the Laboratory of Animal Behavior and Simulation Ecology, Department of Zoology, CCS Haryana Agricultural University, Hisar (India).

Figure 1. A field of rocket crop in the flowering stage.

Figure 2. A flower of rocket with cruciferous petals and corolla tube (source: https://www.inaturalist.org/guide_taxa/338656; accessed on 15 July, 2023).

2.1. Flower Visitors

2.1.1. Assemblage of Flower Visitors

To determine the pattern of assemblage of different insects visiting the blossoms of rocket during its flowering period, the insects were collected by hand net with 30 cm ring diameter. Sweeps were performed during the peak flowering period of crop. The captured insects were killed in potassium cyanide bottle and preserved as dry specimens. The latter were then 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.

2.1.2. Abundances of Flower Visitors

Observations were recorded during the flowering period of this crop. For this purpose, five plots of 1 m^2 size were randomly selected in the crop field (Figure 3).

A total of 16 plots, each 1 m $\times$ 1 m (1 m^2) and scattered at equal distances, were marked 1 m inside the outer boundary of the rocket field and were numbered as given in the layout plan (Figure 3). Of these 16 plots, 5 were selected randomly for recording the number of pollinating insects. Randomization was performed by mixing the numbered balls representing the plots and drawing all lots after adding already drawn balls for providing equal probability to each plot. The order of number of balls in the first draw was (i) 14, (ii) 6, (iii) 2, (iv) 9, and (v) 4 (as shown bearing asterisk sign). The same procedure was followed for the subsequent draws. Observations on the pollinator numbers and their foraging behavior were recorded on the selected plots. All other observations were recorded in the general field of this plant species.

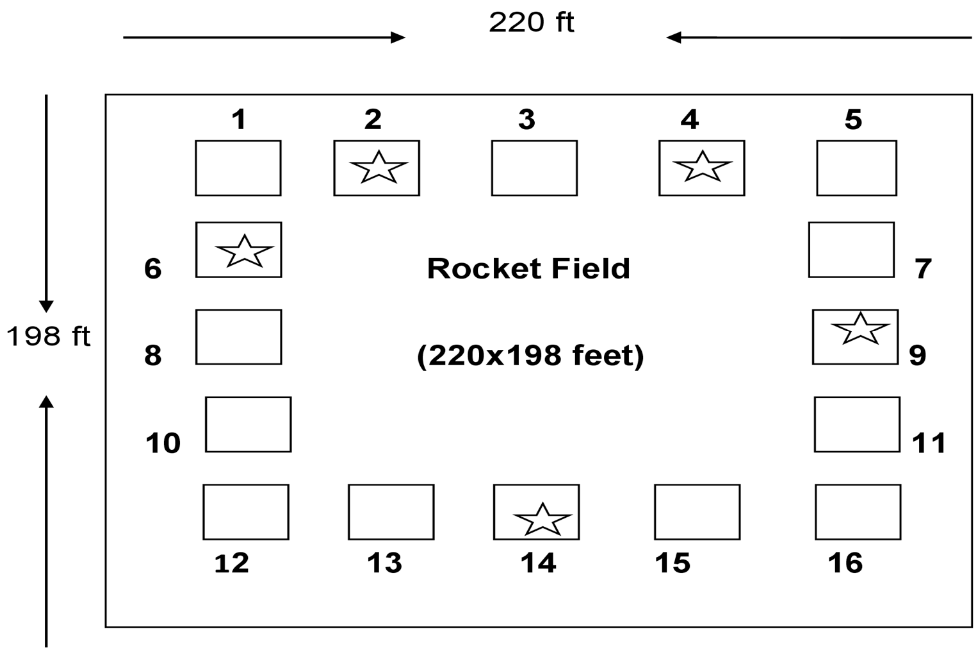

Figure 3. Layout plan of the experiment for recording observations on the number of foraging insects. For example, plots marked with asterisks were randomly selected for the first set of observations.

Observations on plots were recorded while moving clockwise (for example, from plots 2 through 6). A set of time-bound observations was completed within half an hour and was repeated at 2 h intervals starting from 9:00 h to 17:00 h (total of 5 observations on a day). The first observation started when the crop was in a mediocre flowering stage. These daily observations were then repeated at weekly intervals and completed in 5 weeks when flowering started declining (thus total observations = n = (5 × 5 × 5) = 125).

2.2. Foraging Behavior of Flower Visitors

(i) **Foraging modes:** Foraging mode is the method of working by a forager on a flower while harvesting pollen and/or nectar reward [1,47,48]. Based on the foraging modes of the insects visiting the blossoms of the rocket flowers, their foraging behavior was characterized following Sihag [1,47] and Sihag and Shivrana [48], as given below:

P-foragers: These visitors foraged from the top/front of the flower for pollen only in each foraging attempt (Figure 4). Therefore, these visitors always acted as pollinators. These were designated as P-foragers.

NP-foragers: These visitors too foraged from the front/top of the flower for collecting both pollen and nectar in each foraging attempt. Therefore, these visitors also always acted as pollinators. These were designated as NP-foragers.

N-foragers: These visitors foraged from the base/side of the flower from the corolla slit to collect/steal nectar in each foraging attempt. These visitors were nectar thieves and did not pollinate the flowers (Figure 5). These visitors were designated as N-foragers.

(ii) **Foraging rates:** The foraging rate is the number of flowers visited by a forager per minute [1]. The observations on the foraging rates (number of flowers visited per minute) were recorded with the help of a stopwatch (with an accuracy of 0.1 s) on 10 individuals of a species. The observations were recorded five times a day (i.e., at 9:00, 11:00, 13:00, 15:00, and 17:00 h) and were repeated at weekly intervals for five weeks during moderate to peak flowering (total observations, n = (10 individuals × 5 hourly × 5 weekly observations) = 250).

Figure 4. *Apis florea* foraging from the front/top of the flower of the rocket.

Figure 5. *Apis mellifera* thieving nectar while foraging from the side/base of the flower of rocket.

2.3. Loose Pollen Grains Carried by a Flower Visitor and Deposited on the Stigma

To know the number of loose pollen grains borne by a foraging visitor, the method of Sihag [1] was followed. During the peak foraging activity, a forager of a species was captured. After removing its corbicula (pollen basket) if present, the insect was immersed in 10 mL 60% alcohol. The number of pollen grains present in this volume was recorded with the help of a haemocytometer [1]. The observations were repeated on 10 individuals of each species (total number of observations for each species, n = (10 individuals $\times$ 5 squares of a haemocytometer) = 50).

Likewise, to know the number of pollen grains deposited on the stigma of a visited flower by a forager, the method of Bertin [49] was followed. The stigmas of pollinated flowers of rocket, excised after 24 h of their pollination, were brought to the laboratory and stained in acid fuchsine. The pollen grains were counted under × 100 magnification. The observations were recorded on 20 stigmas (n = 20).

2.4. Effect of a Single/Multiple Visit(s) on the Seed Set

To determine how many seeds are produced from a single and multiple visits of a visitor, these observations were recorded. For recording the effect of a single visit by a visitor on the seed set of a visited flower, the method of Spears [36] was used. However, for recording the effect of multiple visits, the method of Donovan and Read [50] was used. Many floral buds that were to open the next morning were marked in the evening. Such flowers, after receiving single and multiple visits from a visitor, were enclosed in nylon yarn net bags with 25 mesh size till seed set (25 mesh size means there were 25 rectangular pores in an area of 1 inch square (i.e., in an area of 254 mm × 254 mm = 645 mm^2, each pore had about 0.5 mm × 0.5 mm size); this mesh size facilitated the ventilation of bags to overcome heating and excessive humidity and also prevented entry of large insects). The siliquas developed from marked flowers were harvested on maturity and set seeds were recorded following Sihag [43].

2.5. Pollen Transfer Efficiency of Flower Visitors

Rocket bears solitary bisexual flowers. Therefore, model equations recommended for such situations were used to derive the pollen transfer efficiency (PTE) of its flower visitors (for details, refer Sihag [1]):

1. **For foragers showing only one kind of foraging mode:**

For foragers showing only one kind of foraging mode (e.g., pollen as well as nectar collection in each foraging attempt leading to successful pollen transfer), the following model equation was used [1]:

$$\mathrm{PTE} = \mathrm{F} \times \mathrm{R} \quad (1)$$

where:

F = foraging coefficient; here, its value is equal to unity. This is because, here, all the foraging attempts would result in successful pollination.

R = foraging rate (defined earlier).

2. **For foragers showing different (more than one) kinds of foraging modes:**

In case of visitors of a species showing more than one kind of foraging mode (e.g., only pollen collection, pollen as well as nectar collection, and only nectar collection), the following model equation was used [1]:

$$\mathrm{PTE} = 1/\mathrm{n}\left[\sum_{i=1}^{n}\sum_{j=1}^{3} \mathrm{P_{ij}} \times \mathrm{F_j} \times \mathrm{R_j}\right] \quad (2)$$

where:

n = number of times the observations were recorded on a day.

R_j = foraging rate of a visitor showing jth foraging mode (j takes value from 1 to 3). For example, R_1 = foraging rate of a visitor collecting pollen only, R_2 = foraging rate of a visitor collecting nectar as well as pollen, and R_3 = foraging rate of a visitor collecting nectar only.

Fj = foraging coefficient for the jth foraging mode, j = 0 or 1. In case of R_1 and R_2, $F_1 = F_2 = 1$ and, in case of R_3, $F_3 = 0$. When a flower visitor is a P-forager, its foraging rate and foraging coefficient are R_1 and F_1, respectively. Likewise, when a flower visitor is an NP-forager, its foraging rate and foraging coefficient are R_2 and F_2, respectively, and, when a flower visitor is an N-forager, its foraging rate and foraging coefficient are R_3 and F_3, respectively. In the latter case, a flower visitor was a nectar thief and did not bring pollination of the visited flower(s).

2.6. Derived PTE versus Real PTE

Real PTE means the number of flowers fully pollinated (that makes them capable of realizing the full reproductive potential of a flower) by an individual of a species per unit of time (e.g., per minute), so that:

$$\text{Real PTE} = \frac{\text{DerivedPTE}}{\text{n}} \quad (3)$$

where:

n = number of pollen-transferring visits required to fully pollinate a flower.

2.7. Statistical Analysis

The experiments of this study were laid down in a completely randomized design [51]. The data were analyzed using one-way analysis of variance [51]. This was followed by a post hoc test for the calculation of the 'Least Significance Difference' (LSD) [51]. With the help of these values, the treatment means were compared at a 5% level of significance.

3. Results

3.1. Flower Visitors of Rocket

Ten insect species visited the flowers of rocket at Hisar during its flowering period (Table 1). Among these insect visitors, there were two species of native solitary ground-nesting bees viz. *Andrena savignyi* Spinola (syn. *Andrena ilerda* Bingh.) and *Andrena leaena* Cameron; two species of native honey bees viz. *Apis dorsata* F. and *Apis florea* F.; and one species of exotic honey bee species viz. *Apis mellifera* L. Moreover, there were three fly species (viz. *Eristalis* sp., *Syrphus* sp., and *Sarcophaga* sp.), one tiger butterfly species (*Danaus genutia* (Cramer)), and one beetle species (*Coccinella septempunctata* (L.)).

Table 1. Insect species visiting the flowers of the rocket at Hisar.

Sr. No.	Insect Species	Insect Type	Order	Family
1.	*Andrena savignyi* Spinola	Solitary Bee	Hymenoptera	Andenidae
2.	*Andrena leaena* Cameron	Solitary Bee	Hymenoptera	Andenidae
3.	*Apis dorsata* F.	Social Bee	Hymenoptera	Apidae
4.	*Apis florea* F.	Social Bee	Hymenoptera	Apidae
5.	*Apis mellifera* L.	Social Bee	Hymenoptera	Apidae
6.	*Eristalis* sp.	Fly	Diptera	Syrphidae
9.	*Syrphus* sp.	Fly	Diptera	Syrphidae
7.	*Sarcophaga* sp.	Fly	Diptera	Sarcophagidae
8.	*Chrysoma bezziana* V.	Fly	Diptera	Calliphoridae
9.	*Danaus genutia* (Cramer)	Butterfly	Lepidoptera	Nymphalidae
10.	*Coccinella septempunctata* (L.)	Beetle	Coleoptera	Coccinellidae

Overall, the assemblage of insect visitors of rocket represented seven families and three orders. Among the visitors, all the bee species were pollen and nectar collectors. Therefore, these were potential pollinators. On the other hand, flies fed on the stigmatic exudates and were casual pollinators. These were, therefore, amalgamated together for the subsequent studies. Butterfly (*Danaus genutia*) was in extremely small numbers and was a casual visitor. Beetle (*C. septempunctata*) was a casual floral visitor, fed on the aphids infesting the stem, branches, and leaves and, therefore, was not a pollinator. The butterfly and beetle were, therefore, excluded from the subsequent studies.

3.2. Loose Pollen Grains Carried by a Flower Visitor and Deposited on the Stigma

Flower visitors of rocket carried different loads of loose pollen grains (Table 2). The pollen grains carried by different pollinator species differed significantly (ANOVA followed by LSD; $p < 0.05$, Table 2). Likewise, pollen grains deposited on the stigma by various pollinators also differed significantly (ANOVA followed by LSD; $p < 0.05$, Table 2).

Table 2. Loose pollen grains carried and deposited by the flower visitors of the rocket.

Visitor Species	Number of Loose Pollen Grains	
	Carried on the Body of a Forager While Foraging on the Plant [a]	Deposited on the Stigma in a Single Visit [b]
Andrena savignyi Spinola	1340 ± 21.2	63 ± 10.2
Andrena leaena Cameron	1315 ± 22.8	55 ± 8.6
Apis dorsata F.	1660 ± 15.8	85 ± 12.8
Apis florea F.	1235 ± 10.3	45 ± 8.2
Apis mellifera L.	1570 ± 15.5	68 ± 12.2
Flies	240 ± 7.6	30 ± 5.3
C.D. ($p < 0.05$)	**22.6**	**6.8**

[a] Mean ± s.e. of 50 observations (10 bees × 5 blocks of haemocytometer), numbers were rounded off to the nearest whole number; [b] mean ± s.d. of 20 observations, numbers were rounded off to the nearest whole number.

From these data, differences could be seen between various pollinators for their contribution toward the reproductive success of rockets (Table 2). However, if examined logically, this ranking seemed erroneous. This is because the flower of rocket has only 24 ovules and is capable of producing a maximum of 24 seeds (this is the female reproductive asymptote of a rocket flower). Except flies, all other visitors carried and deposited a much larger number of pollen grains than required by a flower of rocket. Therefore, some other methods needed to be investigated.

3.3. Seed Set Resulting from a Single and Multiple Visit(s)

Data on the number of seed sets resulting from a single visit of a pollinator exhibiting different foraging modes on the flowers of rocket are presented in Table 3.

Table 3. Seed set resulting from a single visit of different foraging modes of various flower visitors of rocket.

Visitor Species	Number of Seeds Set in the Siliqua of Rocket Due to a Single Visit of Different Foraging Modes of Flower Visitors (Figures in Parentheses Are Percent Siliqua Setting Seeds) [a]		
	Only Nectar Foraging (N)	Only Pollen Foraging (P)	Nectar and Pollen Foraging (NP)
Andrena savignyi Spinola	ba	ba	24.0 ± 0.0 (100)
Andrena leaena Cameron	ba	ba	24.0 ± 0.0 (100)
Apis dorsata F.	ba	24.0 ± 0.0 (100)	24.0 ± 0.0 (100)
Apis florea F.	0 (0)	24.0 ± 0.0 (100)	24.0 ± 0.0 (100)
Apis mellifera L.	0 (0)	24.0 ± 0.0 (100)	24.0 ± 0.0 (100)
Flies	0 (0)	-	-

[a] $n = 40$.

A single visit of a P- or NP-forager (pollen-transferring visit) was sufficient to result in the maximum seed set in a flower. On the other hand, there was no seed setting in the flowers that received visits from the N-foragers (nectar thieves) (Table 3). The seed set resulting from two foraging modes (an NP and a P) as well as due to the bee pollinators were statistically alike/similar and did not differ significantly (based on ANOVA and LSD derived from post hoc test; $p > 0.05$, Table 3). Therefore, based on a single visit, it seemed that all the bee pollinators of rocket salad contributed equally towards the reproductive success of this plant. However, on this count, the contribution of dipterous flies seemed quantitatively quite low as compared to the bee pollinators.

Likewise, data on the number of seed sets resulting from multiple visits of a pollinator on the flowers of rocket are presented in Table 4. A single (pollen-transferring) visit of each bee species could fully realize the reproductive potential of a flower; the multiple visits did not add further to the benefit of this plant species. On the other hand, the effect of a single visit of the dipterous flies was quite low; however, these pollinators added incrementally towards the seed set as the number of visits increased. The differences among the bee visits as well as among the bee species were non-significant (based on ANOVA and LSD derived from post hoc test; $p > 0.05$, Table 4). However, the differences between bees and flies and between visits of flies were significant (based on ANOVA and LSD derived from post hoc test; $p < 0.05$, Table 4). Multiple visits of bees, therefore, were of no use to the flowers of rocket. However, multiple visits of flies were useful to the flowers of this plant species.

Table 4. Seed set resulting from multiple visits of flower visitors of rocket.

Visitor Species	**Number of Seeds Set in the Siliqua of Rocket Due to Multiple Visits of Flower Visitors (Figures in Parentheses Are Percent Siliqua Setting Seeds)** [a]			
	1	**2**	**3**	**4**
Andrena savignyi Spinola	24.0 ± 0.0 (100)	24.0 ± 0.0 (100)	24.0 ± 0.0 (100)	24.0 ± 0.0 (100)
Andrena leaena Cameron	24.0 ± 0.0 (100)	24.0 ± 0.0 (100)	24.0 ± 0.0 (100)	24.0 ± 0.0 (100)
Apis dorsata F.	24.0 ± 0.0 (100)	24.0 ± 0.0 (100)	24.0 ± 0.0 (100)	24.0 ± 0.0 (100)
Apis florea F.	24.0 ± 0.0 (100)	24.0 ± 0.0 (100)	24.0 ± 0.0 (100)	24.0 ± 0.0 (100)
Apis mellifera L.	24.0 ± 0.0 (100)	24.0 ± 0.0 (100)	24.0 ± 0.0 (100)	24.0 ± 0.0 (100)
Flies	2.5 ± 0.02 (6.5)	4.0 ± 0.03 (10.0)	6.5 ± 0.05 (16.25)	8.5 ± 0.07 (21.25)

[a] Based on 40 observations.

3.4. Pollen Transfer Efficiency of the Flower Visitors of the Rocket

Foraging behavior of flower visitors

Different flower visitors of rocket showed different foraging modes (Table 5). Two ground-nesting solitary native bees viz. *Andrena savignyi* and *Andrena leaena* were invariably front/top foragers, as these bees resorted to NP-foraging mode. While visiting a flower of rocket, these bees always pollinated the flowers they visited.

Table 5. Foraging modes, number of foragers, foraging rates, and pollen transfer efficiency of different flower visitors of rocket.

Parameter	**Foraging Mode**	**Visitor Species**					
		Andrenasavignyi	***Andrena leaena***	***Apisdorsata***	***Apis florea***	***Apis mellifera***	**Flies**
Abundance (No. of foragers Per m^2) *	**N**	0	0	0	3.75 ± 0.25	0.90 ± 0.07	ba
	P	0	0	0.25 ± 0.02	1.05 ± 0.07	0.60 ± 0.04	4.32 ± 0.02
	NP	1.65 ± 0.15	1.50 ± 0.14	1.55 ± 0.14	0.35 ± 0.02	2.10 ± 0.14	ba
	N + P + NP	1.65 ± 0.15	1.50 ± 0.14	1.80 ± 0.24	5.15 ± 0.80	3.60 ± 0.25	4.32 ± 0.02
Foraging rate (No. of flowers visited per minute) **	**N**	0	0	0	nt	nt	ba
	P	0	0	7.35 ± 1.6	3.30 ± 0.45	4.55 ± 0.45	0.15 ± 0.001
	NP	8.85 ± 1.5	8.35 ± 1.4	5.5 ± 0.7	1.35 ± 0.13	3.15 ± 0.69	ba
DerivedPTE		**14.6**	**12.5**	**1.8 + 8.5 = 10.3**	**3.4 + 0.5 = 3.9**	**2.7 + 6.6 = 9.3**	**0.65**
Real PTE		**14.6**	**12.5**	**10.3**	**3.9**	**9.3**	**0.03**
Percent pollination by a species		**28.84**	**24.69**	**20.34**	**7.70**	**18.37**	**0.06**

* Mean ± s.d. of 125 observations; ba = behavior absent; nt = nectar thieving; ** Mean ± s.d. of 125 observations; other abbreviations are as in Table 5.

On the other hand, *Apis florea* and *Apis mellifera* exhibited all three kinds of foraging modes (i.e., N, NP, and P). In the latter, honey bee nectar-thieving behavior was more common than other bees (Table 5). However, *Apis dorsata* never resorted to nectar-thieving foraging mode (N-foragers were not present). Based on these observations, the relative contribution of pollinators towards the reproductive success of this plant could not be ascertained. Therefore, knowledge of the foraging behavior of the pollinators was not sufficient for making differences among them in their contribution toward the reproductive success of a plant.

In the present context, pollinator abundance was another parameter that needed to be studied. Abundances of pollinators were distinctly different, as differences between the quantities of this parameter of the pollinators were significant (ANOVA, followed by LSD derived from a post hoc test, $p < 0.05$, Table 5). *Apis florea* was the most abundant species followed by *Apis mellifera*, the flies, *Apis dorsata*, *Andrena leaena*, and *Andrena savignyi* in descending order. However, data on the abundance of pollinators did not confirm their contribution towards the reproductive success of this plant species.

Like abundance, the foraging rates of the pollinator also differed significantly, as differences between them were significant (ANOVA, followed by LSD derived from a post hoc test, $p < 0.05$, Table 5). *Andrena savignyi* was the fastest forager, followed by *Andrena leaena*, *Apis dorsata*, *Apis mellifera*, and *Apis florea*; the dipterous flies were the slowest among these pollinators. However, data on foraging rates also did not confirm the contribution of different pollinators toward the reproductive success of this plant species.

Data in Table 5 reveal that *Apis florea* was the most abundant visitor on the flowers of rocket. However, its foraging behavior and rates made it less efficient. On the other hand, *Andrena savignyi* (syn. *Andrena ilerda*) and *Andrena leaena* were less abundant, but their foraging behavior and rates made them the most efficient pollinators of rocket. Therefore, foraging modes, foraging rates, and visitors' abundance alone could not satisfactorily measure the pollination efficiency of a visitor species. Using data in the first two model Equations (1) and (2), a single value of PTE for a species could be derived. From the latter parameter, using model Equation (3), the real PTE of the pollinators could be determined (Table 5). Based on real PTE, *Andrena savignyi* was found to be the most efficient pollinator of rocket, followed, in a descending order, by *Andrena leaena*, *A. dorsata*, *A. mellifera*, and *A. florea*; the dipterous flies were the least efficient pollinators of rocket.

To ascertain the relative contribution of pollinators of the rocket towards its reproductive success, their percent pollination was derived. In rocket salad, about 28.84% of total pollination was brought by *Andrena savignyi*, 24.69% by *Andrena leaena*, 20.34% by *Apis dorsata*, 18.37% by *Apis mellifera*, and 7.7% by *Apis florea*; the dipterous flies caused only 0.06% pollination. Therefore, all the pollinators of this plant do not contribute equally towards the reproductive success (pollination and seed production) of this plant. From the data in Table 5, it is also amply evident that bee pollination predominated in rocket. However, to accomplish maximal pollination in this species, the diversity of pollinators seemed to be important. However, the most striking feature of this study is the role of native bees in the pollination of rocket. About 81.5% of the total pollination in this species is brought by native bees; the exotic honey bee species, *Apis mellifera*, brought even less than 18.5% of total pollination in this plant (Table 5). Therefore, native bees are the major pollinators of rocket in the semi-arid environments of Northwest India.

4. Discussion

Not all flower-visiting insects are equally important to the plant. Their role as pollinators is variable depending upon their abundance, foraging modes, foraging rates, and the number of pollen grains carried on their body and deposited on the receptive stigma of the flower. Many species of insects visit the flowers of a plant and these show different kinds of foraging behaviors. Their abundances, foraging modes, and foraging rates are different. Many earlier reports confirm these results [1,2,7–18]. Due to differences in these parameters, the visitors' contributions toward the reproductive success of a plant are different. Earlier workers used many diverse methods to measure the contribution of a visitor toward the reproductive success of a plant. In this study, I tried to combine the behavioral data with the seed set of the rocket. The results achieved are distinctive in ranking the contribution of different visitors towards the reproductive success of this plant in terms of pollination efficiency of the flower visitors of this plant.

There are reports that insect pollination increases seed/fruit production in a wide variety of crops [43,52]. Several species of fruits, vegetables, oilseeds, spices and condiments, forages, and fiber crops benefit due to insect pollination. In the absence of bee pollination, seed/fruit production in many crops declines markedly [43,52,53]. Some recent reports reveal that global pollinators have declined [54,55]. Both species diversity and richness of pollinators have declined [56–60] and there is evidence of declines in wild pollinators [5,61–70]. Recent reports from the semi-arid environments of Northwest India reveal that the colony numbers of native wild honey bees (*Apis dorsata* and *Apis florea*) and the foraging populations of native andrenid (*Andrena savignyi* and *Andrena leaena*) and wild honey bees (*Apis dorsata* and *Apis florea*) have declined [5,44,67,68]. Many ecological drivers are potential causes of such declines, including habitat fragmentation [69] and loss [5,70,71], pathogens [72,73], alien species [74], agrochemicals [21,44,75–77], climate change [73,78], and the interactions between them [79–81]. The native bees, which are important pollinators of local plants, are the worst affected. The loss of pollinators has resulted in losses of pollination services. Such losses have significant ecological and economic implications. These could negatively and significantly affect plant diversity, leading to ecosystem instability, crop production losses, food insecurity, and impaired human welfare [82–87].

Earlier reports revealed that the native bees held the key for pollination service in the semi-arid agroecosystems of Northwest India [7–18]. This is because the native bees brought more than 40% of pollination in various crops [1,2,7–18]. Any decline in the richness and diversity of these bees would have very severe adverse effects on plant reproduction and crop seed/fruit production; this would not only threaten food security but also severely affect the wild angiosperm flora [88]. Therefore, the conservation of native bees is very important for the sustainability of not only the agroecosystems but also other terrestrial ecosystems.

The blossoms of rocket attracted 10 insect species; among them, bees were the main pollinators. I utilized the behavioral and seed set data to determine the pollination efficiency of flower visitors of rocket. On this basis, *Andrena savignyi* was found to be the most efficient pollinator of rocket, followed by *Andrena leaena*, *Apis dorsata*, *Apis mellifera*, *and Apis florea.* About 99.9% of pollination in rocket is brought by the bees. Therefore, the melittophilous mode of pollination predominated in this species. Likewise, about 81.5% of pollination is brought by native bees. Therefore, native bees are the major pollinators in rocket in the semi-arid environment of Northwest India. However, pollinator diversity did matter for maximal pollination in rocket, and conservation of this diversity is the need of the hour.

5. Conclusions

This study reveals that native bees are the major pollinators of rocket in the semi-arid environments of Northwest India. This explicitly indicates that, in conservation agriculture, native bees are an important component of the pollination services and play a major role in agroecosystems. The same situation is expected to prevail over the global scale. Viewing their importance in agroecosystems, species of native bees need to be vigorously protected and conserved. Therefore, future research must be directed towards the study of conservation ecology and conservation methods of these pollinators.

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