



RESEARCH ARTICLE - BEES

Leafcutter Bees (Hymenoptera: Megachilidae) as Pollinators of Pigeon Pea (*Cajanus cajan* (L.) Millsp., Fabaceae): Artificial Trap Nests as a strategy for their conservation

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Abstract

Solitary bees of the family Megachilidae are the key pollinators of pigeon pea. Artificial trap nests were used to study nesting parameters, such as occupancy rate, nest establishment time, and building pattern during the vegetative and flowering stages of the *Cajanus cajan* (Fabaceae). The installed traps were occupied by three different leafcutter bees (*Megachile lanata*, *M. laticeps*, *M. disjuncta*) and one parasitic bee *Coelioxys* sp. Bees occupied the nest tubes for 16.01 ± 2.82 and 10.23 ± 2.30 days in the vegetative and flowering stages. We recorded 38.33 and 72.50% trap occupancy rates during crop vegetative and flowering stages, respectively. The percent parasitization by *Melittobia* sp was significantly higher during the vegetative stage (53.67%). Brood cells were parasitized by *Coelioxys* sp (6.67%) during the flowering stage. Many female bees tend to occupy trap nests with active nest construction during the flowering stage (7.21 ± 2.28 bees). In contrast, male bees merely took shelter inside the traps during the vegetative stage. Thus, it is concluded that female bees possess more wing wear during the vegetative stage of the crop when compared to the flowering stage. We also observed a significant increase in the percent pod set, the number of seeds per pod, and 100 seed weight in the experimental plot compared to the control plot, proving the importance of leafcutter bees for the pollination of *Cajanus cajan* crop. The present study results confirmed the role of artificial trap nests in providing habitats for the solitary leafcutter bees, thereby increasing their activity and nest abundance, which favors the pollination and better yield in pigeon pea.

Introduction

Most solitary bees named Megachilidae construct their nests in pre-existing natural cavities like hollow stems, dead woods, and manmade holes using materials like leaf, mud, resin, and chewed plant tissues (O'Neill, 2001; Cane et al., 2007). Leafcutter bees use leaf bits or plant resin to line their brood cells (Litman et al., 2011; MacIvor, 2016). These bees possess an unusual nesting habitat preference, such as nesting in the fallen flowers of *Markhamia lutea* (Amala et al., 2017) and petioles of papaya (Amala et al., 2019). Usually, they cut the leaves in different shapes to line the brood cells and

lay their eggs inside the leaf cell pre-provisioned with pollen (Raw, 2004; Buschini, 2006; Michener, 2007). Trap nests were widely used to manage other Megachilidae wild bees like *Osmia cornifrons* (Maeta & Kitamura, 1974), *O. bicornis* (Gruber et al., 2011), *O. lignaria* (Bohart, 1972; Philips & Klostermeyer, 1978), *O. cornuta* (Bosch & Kemp, 2002) and *M. rotundata* (Bohart, 1972; Fairey et al., 1989; Pitts-Singer & Cane, 2011). Trap nests were also utilized to monitor the nesting behavior of bees, their pollen/prey preference, their natural enemies in agro-ecosystem (Roubik & Villanueva-Gutierrez, 2009; Ercit, 2014). An additional study conducted by Junqueira et al. (2012) reported that erecting bee shelters



with suitably sized bamboo stalks can enhance the population of nesting carpenter bees by >200% over 23 months with the active emergence of new broods.

Pigeon pea (*Cajanus cajan* (L.) Millsp., Fabaceae) is an often-cross pollinated crop. It attracts several bee pollinators, leading to potential yield enhancement (Abrol & Shankar, 2015). Interestingly, leafcutter bees of the genus *Megachile* were reported to be the key pollinators of pigeon pea as they are capable of ‘flower tripping’ behavior to access pollen of leguminous crops. Hence, providing nesting structures amidst the cropped area would lead to suitable foraging and shelter, with the consequent conservation of solitary bees populations (Gathmann et al., 1994; Peterson & Roitberg, 2006; Joshi et al., 2020). Due to the increasing loss of biodiversity of pollinators, there is a growing need to modify agricultural landscapes to restore the biodiversity of bee pollinators (Villemey et al., 2018). The present study was conducted to test the hypotheses that nesting activity of leafcutter bees, pollination, and yield of pigeon pea during the vegetative and flowering stages can be influenced by providing artificial nesting structures.

Materials and Methods

Study Site

The present study was carried out in the experimental farm of ICAR-National Bureau of Agricultural Insect Resources (NBAIR) Yelahanka Campus, Bengaluru (13.096792N, 77.565976E), Karnataka, India, during the year 2019 (July to December). The study area of 22 acres comprising of cultivated croplands with various annual crops like cereals and pulses, orchard blocks of mango (*Mangifera indica*), sapota (*Manilkara zapota*), and cherimoya (*Annona cherimola*). Also,

two patches of pollinator gardens of about 1.5 acres with over 100 plant species of diverse plant families were part of this study location, which is right in the heart of a rapidly growing high-tech-city and capital of the southern Indian state of Karnataka. Pigeon pea, *Cajanus cajan* crop (Var. BRG-1) was cultivated on 0.5 acres. We adopted a standard package of practices recommended for pigeon pea cultivation in the region by the State Agricultural University. An inter-row spacing of 60cm and plant to plant spacing of 15cm was adopted during seeding. Care was taken not to apply pesticides to manage any insect pests as it may affect the activity of the bees in this experimental plot. The observations were recorded from July to September (vegetative stage), mid-October to November (flowering stage), coinciding with the peak flowering of the crop.

Trap Nests

Two plots of pigeon pea were maintained, one installed with trap nests and another without trap nests. Bamboo trap nests were installed during the vegetative and flowering stages of the crop. The artificial trap nests consist of bamboo culms of 15 mm in diameter, measuring 200 mm in length. A total of 120 trap nests made of bamboo were organized into ten different nest bundles. Each bundle of a nest with 12 bamboo culms was installed using a wooden pole in the study site during the pigeon pea’s active vegetative and flowering stage. A total of 10 nest bundles were installed in the study area (Fig 1). Before installing the trap nests, the culms were split longitudinally into two halves to facilitate the easier examination of nests once they get occupied by the insects. The split halves were joined firmly using sticky tape. The trap nests were closed at one end with cotton wool and installed with the open end projecting out.



Fig 1. a. Trap nest installation in a *Cajanus cajan* (L.) Millsp. (Fabaceae) plantation of the experimental farm of ICAR-National Bureau of Agricultural Insect Resources (NBAIR) Bengaluru, Yelahanka Campus, India. **b.** Leaf cutter bee, *Megachile* Latreille, 1982 entering trap nest with a leaf bit.

Nesting parameters of solitary bees

The trap nests were monitored daily for occupancy by the insects for 30 days. The inhabited nest tubes were recorded and removed to be studied, and new ones replaced the removed nest tubes after being occupied by the insects in a bundle. The plug material used by the insect to cap its nest and plug appearance was also recorded. The occupied nests were checked for the presence of bees sheltering inside and the presence of active nests. The occupied nests were gently opened by cutting the sticky tape to examine the inner contents. The percent occupancy rate of trap nests at the vegetative and flowering stages was recorded. The material used to construct nests and partition the cells was observed and recorded. The number of male and female bees that occupied the trap nests during the vegetative and flowering stage was also recorded. The number of days the bees took to occupy the nest tubes after installation and the time to complete the nest construction were recorded. The trap occupancy rate was calculated by taking the ratio of the number of occupied tubes per bundle of the nest and the total number of tubes per bundle of the nest. The occupied nest tubes were collected and brought to the laboratory and placed inside polyethylene bags fastened with a rubber band to prevent the escape of emerging adult bees. The occupied nest tubes were observed daily, and the emerged adults were collected and dry preserved for taxonomic identification. The number of days taken from the end of nest closure to the emergence of adult insects from the trap nests was also recorded. The number of cells constructed by female bees inside the nest and the number of emerged bees per nest from the trap nests were recorded. Non-emerged bees were examined for signs of brood parasitization and kept separately in aerated containers for the emergence of parasitoids.

Estimation of wing wear of foraging female bees

The activity of female bees in the flowers was recorded during the vegetative and flowering stages of the crop. The foraging bees were collected using entomological nets at weekly intervals at six different time points viz., 8.00 am, 10.00 am, 12.00 pm, 2.00 pm, 4.00 pm, 6.00 pm. The wing wear of the foraging females was evaluated according to Mueller & Wolf-Mueller (1993). A scale of 0 to 5 was attributed to wing wear, where 0 = a completely intact apical margin; 1 = 1–2 nicks on the apical margin; 2 = 3–10 nicks on the margin; 3 = some wing margin intact, though heavily serrated, with >10 nicks; 4 = completely serrated with no apical wing margin intact, but with excisions less than half the width of the distal submarginal cell; 5 = wing as described in 4, but with excisions more than half, but less than the entire width of the distal submarginal cell.

Diversity of Megachile bees

The diversity indices of the genus *Megachile* Latreille, 1802 bees occupying the trap nests during the vegetative and flowering stage were calculated. The total number of solitary

bees occupying the nests and emerging was recorded for 30 days at weekly intervals. The diversity indices were calculated using the PAST software. Shannon Wiener diversity index (Shannon & Wiener, 1949), taking into account the number of individuals as well as the number of taxa indicated by $H = -\sum((n_i/n) \ln(n_i/n))$ where, n_i is the number of individuals of taxon 'i'. Simpson's index is also a measure of diversity that considers the number of species present and the relative abundance of each species. Margalef's richness index: $(S-1)/\ln(n)$, was also calculated where S represents the number of taxa and n is the number of individuals. Evenness index measures the distribution of a species in an ecosystem and was calculated using Pielou's (1966) formula eH/S , where H indicates the Shannon Wiener index and S indicates the number of taxa.

Effect of the visitation by Megachile spp. on the yield of pigeon pea

The effect of the installation of trap nests to increase the abundance of leafcutter bees over the pollination and yield of pigeon pea was studied. We compared the yield and pod set parameters in two plots, one with trap nests installed (treatment plot) and the other without trap nests (control plot). The pollination efficiency of *Megachile* sp in pigeon pea was assessed exclusively by bagging 100 mature flower buds (5 mature buds per 20 different plants) a day before the experiment. The bagged flower buds were opened the next morning during the bright sunshine hours and allowed for single visitation by the leafcutter bees foraging near the artificial traps. The flowers were observed, and those visited by the leafcutter bees were labeled and bagged after the visitation. The fruiting rate due to the visitation by leafcutter bees was assessed using the formula,

$$\text{Percent pod set} = \text{PL-PB/PL} \times 100$$

where PL denoted pods set in flowers visited by leafcutter bees, PB denoted pods set in bagged flowers.

In both the plots, the pods were collected from the 20 marked plants at maturity. The number of seeds per pod, the percent pod set, number of seeds set per pod, and 100 seed weight (g) were recorded by bagging the flowers (FB) and by allowing flower visitation by the leafcutter bees (FL).

Data analysis

Analysis of variance (GLM in SAS 9.3; SAS Institute, Cary, NC) was used to compare the effect of the leafcutter bee artificial nests (trap nests) on the pollination and yield of pigeon pea. Mean percent acceptance of trap nests, the emergence of bees, and the number of male and female bees that emerged were also analyzed. When a significant difference was detected, treatment means were separated using Tukey's HSD Test (0.5%).

Results

Trap occupancy by the leafcutter bees (Megachile spp.)

The installed artificial trap nests were occupied by insects belonging to different taxa viz: Megachilinae (bees),

Eumeninae (wasps), and Araneae (spiders). Three species of leafcutter bees, *Megachile lanata* (Fabricius, 1775); *M. laticeps* Smith, 1853; *M. disjuncta* (Fabricius, 1781 and one parasitic bee, *Coelioxys* sp. were observed to occupy the installed trap

nests (Fig 2). *Megachile disjuncta* used resin, resin + mud, and cellophane-like membrane to plug its nests. *M. laticeps* used leaf bits to construct and plug its nest entrance. *M. lanata* used leaves and sand to construct and plug its nest entry.

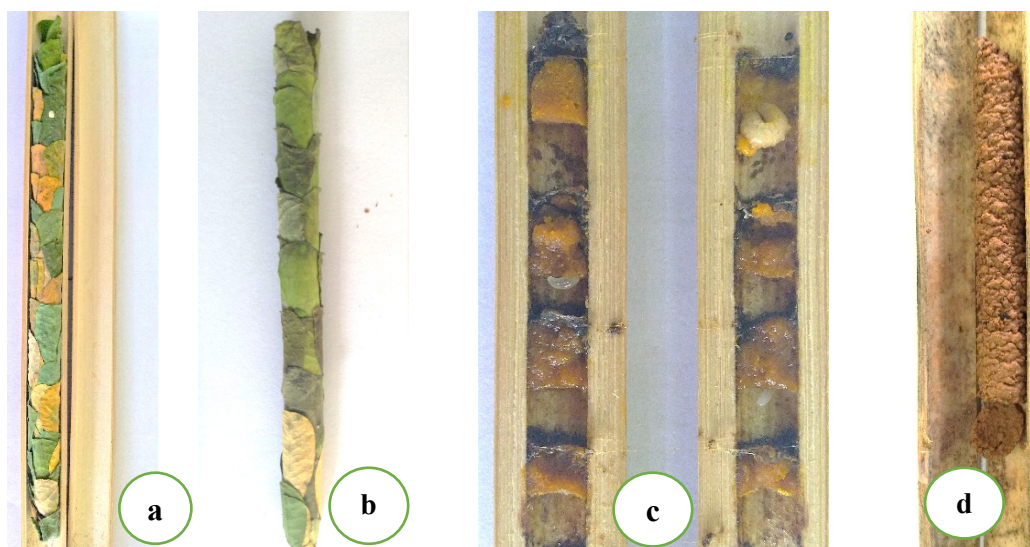


Fig 2. Different types of nesting materials used by bees *Megachile* Latreille, 1982 in a *Cajanus cajan* (L.) Millsp. (Fabaceae) plantation of the experimental farm of ICAR-National Bureau of Agricultural Insect Resources (NBAIR) Bengaluru, Yelahanka Campus, India; **a.** and **b.** leaf bits **c.** resin **d.** mud.

Trap nests had a significant influence on trap rate occupancy by bees during the crop vegetative and flowering stages (F value = 84.03; $P < 0.0001$) (Table 1). The trap occupancy rate was higher during the flowering (72.50%) than in the vegetative stage (38.33%). The mean number of trap nests occupied, the number of active nests recovered, and the number of nests half-filled by bees during the vegetative stage was 17, 12, and 17, respectively (Fig 3).

On the contrary, 43 trap nests were occupied during the flowering period, with 31 active nests and 13 half-filled nests. During the vegetative stage, the male bees were homing

inside the tubes more than the female bees. Such males occupied nest tubes lacked built-in cells, and these male bees were observed to take mere shelter inside the nest tubes. While no active nest construction was observed in the traps during the vegetative stage, the active nests were recovered from the tubes during the flowering stage. The collected nests were built using leaves, resin, and soil material. The female bee used the leaves of pigeon pea specifically for their nest construction. There was a significant difference in the trap occupancy rate by non-bee insects, viz., spiders (F value = 13.50; $P < 0.0001$) and the wasp (F value = 14.23; $P < 0.0001$)

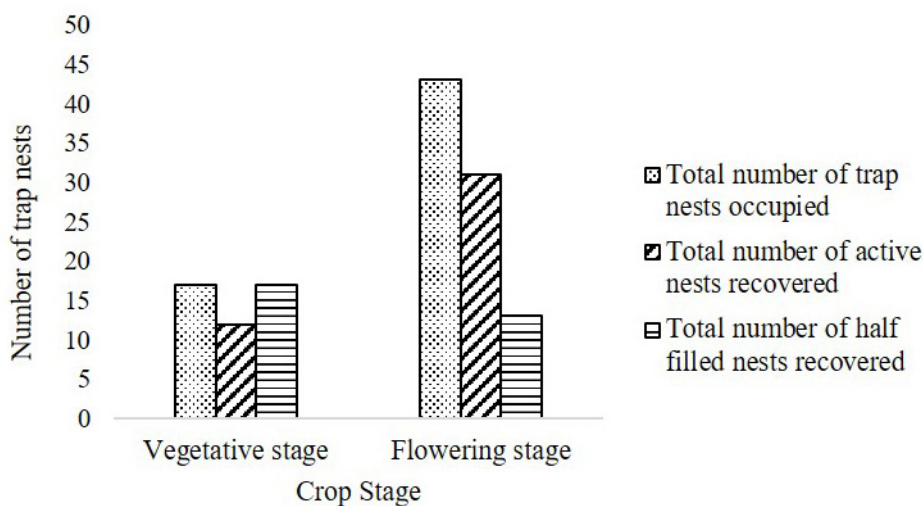


Fig 3. Number of trap nests by leaf cutter bees *Megachile* Latreille, 1802 occupied at two different crop stages of Pigeon pea (*Cajanus cajan* (L.) Millsp. Fabaceae) plantation of the experimental farm of ICAR-National Bureau of Agricultural Insect Resources (NBAIR) Bengaluru, Yelahanka Campus, India.

Table 1. Trap occupancy details of leafcutter bees *Megachile* Latreille, 1802 at two different crop stages of Pigeon pea (*Cajanus cajan* (L.) Millsp., Fabaceae) in the experimental farm of ICAR-National Bureau of Agricultural Insect Resources (NBAIR) Bengaluru, Yelahanka Campus, India.

Crop Stages	Trap occupancy rate by <i>Megachile</i> bees (%)	Trap occupancy rate by spiders (%)	Trap occupancy rate by wasps (%)
Vegetative stage	38.33b	3.33b	2.22b
Flowering stage	72.50a	13.33a	14.47a
F value	84.03	13.50	14.23
P value	P < 0.0001	P < 0.0001	P < 0.0001

during the vegetative as well as flowering period. Spiders' percent trap nest occupancy was 3.33 and 13.33 during the vegetative and flowering stages, respectively. The Eumenid wasp trap occupancy rate was 2.22 and 14.47 during the vegetative and flowering stages.

The number of days taken by the bees to occupy the nest differed significantly between the vegetative and flowering stage (F value = 16.38; P < 0.0001) (Table 2). During the vegetative stage, the traps were occupied for 16.01 ± 2.82 days, whereas, during the flowering stage, the bees occupied the nests for 10.23 ± 2.30 days. The nest completion time significantly varied between the vegetative and flowering stages (F value = 36.10; P < 0.0001). After occupying the nest tubes, the nests were completed in 6.20 days during the vegetative stage and 2.40 days during the flowering stage.

There was a significant difference in the number of cells formed (F value = 15.62; P < 0.0001) and the number of emerged bees per nest (F value = 13.23; P < 0.0001) in the trap nests during the vegetative and flowering stage of the crop. The mean number of cells formed by the bees per nest was 1.60 ± 1.14 and 5.60 ± 0.54 during the vegetative and flowering stages, respectively. The number of bees that emerged per nest during the vegetative and flowering stage was 0.4 ± 0.54 and 5.00 ± 0.71 , respectively. The average number of male bees observed to occupy and take shelter inside the nest tubes during the vegetative and flowering stages was 6.23 ± 0.5 and 1.21 ± 0.8 , respectively (Fig 4). The mean number of female bees observed to occupy and found involved in constructing the brood cells in the nest tubes during the vegetative and flowering stages was 1.01 ± 0.71 and 7.21 ± 2.28 , respectively.

Table 2. Nest development parameters of leafcutter bees *Megachile* Latreille, 1802 at two different crop stages of Pigeon pea (*Cajanus cajan* (L.) Millsp., Fabaceae) in the experimental farm of ICAR-National Bureau of Agricultural Insect Resources (NBAIR) Bengaluru, Yelahanka Campus, India.

Crop Stages	Number of days to occupy the nest	Number of days to complete the nest	Number of cells formed per nest	Number of bees emerged per nest	Percent parasitization of brood cells
Vegetative stage	$16.01 \pm 2.82a$	$6.20 \pm 0.84a$	$1.62 \pm 1.14b$	$0.41 \pm 0.12b$	53.67a
Flowering stage	$10.23 \pm 2.30b$	$2.40 \pm 0.55b$	$5.61 \pm 0.55a$	$5.00 \pm 0.71a$	6.67b
F value	16.38	36.10	15.62	13.23	3.27
P value	P < 0.0001	P < 0.0001	P < 0.0001	P < 0.0001	P < 0.0001

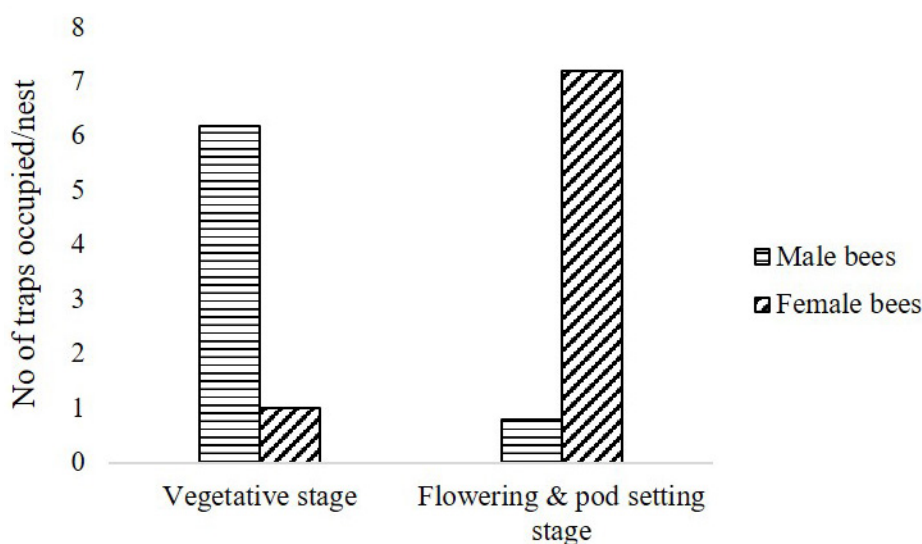


Fig 4. Number of traps occupied by male and female bee *Megachile* Latreille, 1802 at two different crop stages of Pigeon pea (*Cajanus cajan* (L.) Millsp. Fabaceae) plantation of the experimental farm of ICAR-National Bureau of Agricultural Insect Resources (NBAIR) Bengaluru, Yelahanka Campus, India.

Natural parasitization by *Melittobia* sp (53.67%) occurred in nest tubes during the vegetative crop stage. Parasitization by *Coelioxys* sp (6.67%) in the brood cells in the occupied nest tubes collected during the flowering stage was recorded (Table 2). The adult parasitoids emerged from the brood

cells collected from the nest tubes. The age categorization during the vegetative and flowering stage was recorded and presented in Fig 5. The sampling of the female bees during the vegetative stage belonged to the wing wear category of 3 to 5. On the contrary, during the flowering stage, the foraged females belonged to the wing wear category of 0 to 2.



Fig 5. Classification of foraging female of leaf cutter bees *Megachile* Latreille, 1802 as per wing wear in studied specimens from the experimental farm of ICAR-National Bureau of Agricultural Insect Resources (NBAIR) Bengaluru, Yelahanka Campus, India.

Diversity of leafcutter bees (*Megachile* spp.)

Four species of solitary bees were observed occupying the trap nests. The data revealed that a higher diversity of solitary bees was recorded during the flowering stage than the vegetative stage (Table 3). In the present study, the Simpson and Shannon Wiener diversity indices recorded during the vegetative stage were 0.68 and 0.47, respectively. The Simpson (1.33) and Shannon Wiener diversity indexes (0.72) were higher during the flowering stage. The evenness index recorded during the flowering stage (1.01) was higher than during the vegetative stage (0.98). The richness index of the trap nesting bees recorded during the vegetative and flowering stages was 0.68 and 0.98, respectively.

Effect of *Megachile* spp. visits over the pollination and yield of pigeon pea

The contribution of leafcutter bees to the pollination and yield of pigeon pea was recorded (Table 4). It was observed

that there was a significant difference in the percent of pod set due to the pollination by leafcutter bees in the plots installed with and without trap nests (F value = 17.75; P value < 0.0001). The percent pod set in the plots installed with and without trap nests were 62.70 and 38.06, respectively. The number of seeds per pod (F value = 26.75; P value < 0.0001) and test weight (F value = 90.85; P value < 0.0001) of harvested seeds differed significantly between the plots with and without trap nests. The mean number of seed set per pod from the plants in the plot with and without trap nests were 5.76 ± 0.43 and 3.24 ± 0.78 , respectively. Simultaneously, the seed weight from plots with trap nests recorded a significantly greater 100 seed weight (11.37 ± 0.87 g) than the control plot (8.31 ± 1.75 g).

Discussion

Four different species of solitary bees occupied the artificial trap nests installed in pigeon pea cultivation. Other insects like spiders and Eumenid wasp were also observed to

Table 3. Diversity indices of leafcutter bees *Megachile* Latreille, 1802 in different crop stages of Pigeon pea (*Cajanus cajan* (L.) Millsp., Fabaceae) in the experimental farm of ICAR-National Bureau of Agricultural Insect Resources (NBAIR) Bengaluru, Yelahanka Campus, India.

Crop Stages	Simpson's Index	Shannon-Wiener diversity index	Evenness index	Margalef richness index
Vegetative stage	0.68	0.47	0.98	0.68
Flowering stage	1.37	0.72	1.01	0.98

Table 4. Pollination efficiency of leafcutter bees *Megachile* Latreille, 1802 and yield parameters of pigeon pea (*Cajanus cajan* (L.) Millsp., Fabaceae) in the experimental farm of ICAR-National Bureau of Agricultural Insect Resources (NBAIR) Bengaluru, Yelahanka Campus, India.

Treatments	Percent pod set	Number of seeds per pod	100 seed weight (g)
Plots installed with trap nests	62.70a	5.76 ± 0.43a	11.37 ± 0.87a
Control plot	38.06b	3.24 ± 0.78b	8.31 ± 1.75b
F value	17.75	26.75	90.85
P value	P < 0.0001	P < 0.0001	P < 0.0001

occupy the trap nests. Gathmann et al. (1994) reported fourteen species of Apoidea, four species of Sphecidae, one species of Eumenidae, and four species of parasitoids reared from the reed internodes of the grass *Phragmites australis* (Cav.) Trin. ex Steud. (Poaceae). Solitary bees like *Megachile* sp., *Xylocopa tenuiscapa* Westwood, *Amegilla zonata* Linnaeus, and *Nomia* sp. were the major pollinators of pigeon pea in Nagaland, India (Singh, 2016). Chaudhary & Jain (1978) reported *Megachile lanata* as the major pollinator of pigeon pea.

The number of days taken by the bees to occupy the nest and complete the nest was significantly lesser during the flowering stage compared to the vegetative stage. The number of emerged bees per nest was significantly higher during the flowering stage compared to the vegetative stage. This can be attributed to the greater amount of food available in the area, which allowed more females to actively build their nests in the area during the flowering stage. The foraging patch of female leafcutter bee, *M. lapponica*, closer to its trap nests was reported by Gathmann & Tschardtke (2002). Conversely, more male bees were observed occupying per nest during the vegetative stage. Availability of lush green pigeon pea leaves serving as a nesting material with copious pollen-filled flowers might be the reason for more female bees constructing their nests during the flowering stage. It was observed in three solitary bee species (*Anthophora plumipes* (Pallas), *Habropoda tarsta* (Anthophoridae), and *Eucera nigrilabris* Lep. (Eucerinidae), the proportion of ‘near’ visits was twice higher for females indicating that males performed more ‘far’ flights than females (Neeman et al., 2006).

Consequently, males flew longer inter-floral distances than females. Therefore, the energy expended by males during foraging activity must have been higher than that of females, indicating a lower foraging efficiency of males. The availability of specific materials for their nest construction and pollen for larval food are the pre-requisites for successful reproduction in solitary bees (Westrich, 1996). Regarding *Megachile*'s natural enemies, the broods were parasitized by *Melittobia* sp (Hymenoptera: Eulophidae) in the vegetative stage and *Coelioxys* sp (Hymenoptera: Megachilidae) in the flowering stage of the crop. A significantly higher rate of parasitization of the brood cells was recorded during the vegetative stage than the flowering stage. As the proportion of female bees was significantly lesser in the trap nests during the vegetative stage of the crop, the brood care was significantly lower, which

would have resulted in easier invasion by the brood parasites. The brood care by female leafcutter bees by capping its nest with layers of mud/leaf bits to evade attack by predators/parasites was reported by Peterson et al. (2016). A parasitism rate of 85.55% by the parasitoid, *Melittobia hawaiiensis* Perkins, 1907 on broods of leafcutter bees in the trap nest of *Ipomea* reeds was reported by Veeresh Kumar et al. (2015). Sabino & Antonini (2017) reported 15% parasitization of brood cells of leafcutter bee, *Megachile (Moureapis) maculata* inside the trap nests in a montane forest by cuckoo bee *Coelioxys (Acrocoelioxys)* sp. Therefore, providing the trap nests in the agricultural cropped area helps in the dual advantage of conserving the solitary bees by providing habitats and attracting solitary predatory wasps for nesting resulting in biological control of pest insects infesting pigeon pea.

Wing wear of female leafcutter bees was reported to have a negative impact on the foraging ability and reproductive performance of the bees (Foster & Carter, 2010; Rehan & Richards, 2010). In the present study, wing wear occurred more during the vegetative period, and the female bees were observed to make more foraging flights in the crop from the leaf material. Due to the lack of pigeon pea flowers, the bees have to engage in pollen foraging trips far away from the crop, resulting in wing wear during the vegetative period. This increased wing wear could be correlated with the reduction in the nesting success of the female bees, as evident from the low number of nests recovered in the artificial traps during the vegetative period. Greater wing wear was reported to be linked with the reduced foraging success and sustainability of nesting performance of alfalfa leafcutting bee, *Megachile rotundata* (Fabricius, 1787) (Neill et al., 2015). Hence, the reason for the lowest wing wear during the flowering period might be due to the instant availability of patches of flowers of pigeon pea for pollen foraging.

The diversity indices of the solitary bees that occupied the trap nests during the vegetative and flowering stage were presented in Table 3. Shannon's index indicates both abundance and evenness of the species occurring in a community. The abundance of solitary bees was higher during the flowering stage due to the abundant pollen source from the blooming flowers of pigeon pea. The evenness index measures the distribution of a species in an ecosystem. The higher evenness index recorded during the flowering stage indicated the uniform distribution of solitary bees compared to the vegetative stage.

A higher richness index was recorded during the flowering stage, which indicated an increased number of different species of trap nesting bees compared to the vegetative stage. Trap nests as an effective tool to investigate the species assemblage and community structure of cavity-nesting solitary bees were reported by Buschini (2006). Smaller solitary bees prefer to construct their nests near the floral resources rather than foraging for nectar and pollen at far distances, unlike large-sized bees (Wcislo & Cane, 1996; Greenleaf et al., 2007; Franceschinelli et al., 2017).

In the present study, the percent pod set, number of seeds per pod, and 100 seed weight by the pollination of leafcutter bees were significantly higher in the plots where the trap nests were exposed compared to plots without trap nests. The females actively foraged over the opened flowers and returned to the nest in the plots installed with the trap nests. The examination of trap nests during the flowering stage revealed the presence of active broods inside the nests. The foraging bees were loaded with pollen in their abdominal scopa while entering the trap nests. The number of pollinating visits performed by leafcutter bees touching the stigmal surface of the flowers was significantly higher compared to the control plot. Junqueira et al. (2013) reported that the installation of trap nests significantly increased the population and flower visitation of carpenter bees in passion fruit at Minas Gerais, Southeastern Brazil. The introduction of trap nests was reported to increase the densities of solitary bees belonging to the family Megachilidae in apples, almonds, and alfalfa (Bosch & Kemp, 2002).

Usually, successful habitat management measures depend on factors like elevation, land fragmentation, source habitats, and the prevalence of nesting resources like dead woods to conserve solitary bees (Murray et al., 2009; Scheper et al., 2013). Thus, providing nesting sites with rich pollen sources by the presence of a varied melitophyllous flora near the nesting site allows the solitary female bees to save time and energy budgets in foraging and enables them to spend more time in their nests thereby evading the attack by predators and parasitoids (Batra, 1984). Westrich (1989) reported that the availability of pollen sources plays a major role in the prevalence and structuring of bee communities rather than nectar source plants.

Conclusion

Our study shows the leafcutter bees being the key pollinators of pigeon pea. The installation of trap nests helped to increase their population, nesting activity, thereby increasing the flower visitation and pollination in pigeon pea. The trap nest installation in farmlands is an easiest way and also helps in the *in-situ* conservation of the leafcutter bees.

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Authors contribution

AU: conceptualized, conducted, and recorded field observations in the study.

TMS: assisted in drafting the manuscript. Both the authors have read and approved the manuscript.

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