Diversity and ecological role of insect flower visitors in the pollination of mangroves from the Indian Sundarbans

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Sundarban Biosphere Reserve is one of the most important mangrove zones with a vast range of floral and faunal diversity. The present study explores the plant–pollinator relationship among four true mangrove plants, viz. *Avicennia officinalis*, *Avicennia marina*, *Aegiceras corniculatum* and *Aegialitis rotundifolia*, and also includes insect visitor diversity and foraging activities of common insect flower visitors of these plants with their efficiency as pollinators. Though each plant is self-compatible for pollination, the activity of flower visitors helped with superior reproductive success. Among the common five visitors, viz. *Apis dorsata*, *Apis mellifera*, *Chrysomya megacephala*, *Danaus chrysippus* and *Micraspis discolor*, *A. dorsata* showed the highest visitation rate (VR) for each plant and *M. discolor* showed the lowest VR but highest handling time (HT) in all the four mangrove plants. Each flower visitor showed significantly different VR among the plants. In the case of HT, only *A. mellifera* showed significant variation among plants. *A. dorsata* and *A. mellifera* showed maximum pollen carrying efficiency compared to the others. These findings emphasize the role of insect flower visitors in pollination, leading to the perquisite for the protection of mangroves of the Indian Sundarbans.

Keywords: Foraging efficiency, handling time, insect flower visitors, mangroves, visitation rate.

MANGROVES, the only halophyte-dominated, intertidal ecosystem situated at the convergence of land and sea, have been heavily used traditionally for the basic needs of humans such as food, timber, fuel and medicine. Mangroves presently occupy about 181,000 sq. km of the tropical and subtropical coastline worldwide. Approximately one-third of mangrove forests in the world has been lost over the past 50 years[1]. The distribution of this unique ecosystem in the intertidal zones of tropical and subtropical regions of the world is fragile but diversified[2,3]. Hence conservation of this ecosystem should be the primary task for ecologists. Though mangrove forest holds less species richness than other tropical forests and is architecturally simpler than rainforests, but because of its unique ecosystem structure it is highly productive and holds a great diversified faunal resource[1,4]. Mangrove flora and vegetation were first studied by Hamilton and Snedakar[5] and later by Tomlinson[6]. The focus of research regarding mangrove reproductive biology has almost exclusively been on the fruit dispersal stage[7], but surprisingly little is known about its pollination biology. The plant–pollinator relationship is one of the important phenomena in reproduction of the angiosperm flowers, and it is often labelled as a tightly coevolved and mutualistic relationship[8]. With the variations in flower morphology such as size, colour, scent, nectar and pollen, the angiosperm flowers encourage diversity in pollinating species[9]. Pollination ecology plays a major role in the characterization of floral structure and the behaviour of foraging animals, which provides information about the structure of the plant community and adaptability of the visitors to flowers related to the mechanism of pollination[10,11]. Pollinator plays an important role in the breeding mechanism of some plants[12]. The diversified flower visitors of mangroves mostly selected with the generalized pollination system. Due to remote locations, harsh environmental conditions and less availability of pollination resources, insect visitors are associated with plants with a broad spectrum, i.e. most of the plants are not dependent on a particular type of pollinator, but in some cases they may be dependent upon some class of the pollinators[13].

Among all the mangrove forests in the world, Sundarbans, which occupies about 10,000 sq. km (UNESCO; https://whc.unesco.org/en/list/798/), is the largest and one of the most productive and taxonomically diversified mangrove forests. With a unique ecosystem, this forest is divided between two countries, viz. Bangladesh and India. The Indian part consists of almost 40% of the forest and the rest is in Bangladesh[14,15]. This World Heritage Site consists of 24 true or major mangroves[16].

The present study focuses on the diversity of insect pollinators of four true mangrove species, viz. *Avicennia officinalis* (AO), *Avicennia marina* (AM), *Aegiceras corniculatum* (AC) and *Aegialitis rotundifolia* (AR) from the Indian Sundarbans. The information generated from this study will serve as baseline data regarding foraging

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activity of the common flower visitors that will ultimately help in the identification of the most efficient flower visitors/pollinators of these plants from the Sundarbans.

Materials and methods

Studied plants

The study was performed on four ecologically important true Indian mangroves, viz. AO, AM, AC and AR on the basis of the pollination system and ecological role of insects in their pollination. Only a few studies have been done on the insect pollination of these plant species from the Sundarbans mangrove[3,17–19].

Avicennia officinalis Linnaeus (family Aviceniaceae) is an evergreen and dominant mangrove species. It is a moderate size tree with height of almost 15–20 m, stem up to 100 cm in diameter, bark smooth and whitish-grey, pneumatophores many and simple. Leaves are 6–10 cm × 3–6 cm in size with broadly ovate–oblong structure. The flowering season is early May to early July. The star-shaped flower (almost 11 mm long and 8 mm in diameter) is yellow in colour, and panicle inflorescence with five sepals. Pollen is creamy in colour[20,21].

Avicennia marina (Forsk.) Vierh. (family Avicenniaceae) is a tree with irregular branches. It grows to more than 8 m in height, bark is smooth yellowish-brown in colour, leaves elliptic–oblong in shape and 3–6 cm × 2–2.5 cm in size with the upper portion of the leaves showing pale green colour. The flowering season is late April to early July. The size of the flower is almost 6 mm long and 4 mm in diameter and is pale or orange–yellow in colour. The flower is complete bisexual, regular, cyclic with four petals and five sepals[21–23].

Table 1. Study areas in Sundarban Biosphere Reserve, India

Islands	Study areas
Gosaba Island	Pakhirala (22°07.959′N, 088°49.542′E) Jotirampur (22°09.099′N, 088°50.728′E) Paschimpara, Dulki (22°07.956′N, 088°48.946′E)
Satjelia Island	Binapani (22°08.507′N, 088°51.610′E) Satjelia Bazar (22°10.063′N, 088°52.504′E) 4 No. Satjelia (22°09.328′N, 088°53.552′E)
Bali Island	Vidya forest (22°05.681′N, 088°45.872′E) 9 No. Gheri (22°05.335′N, 088°45.552′E) Banidhal (22°08.150′N, 088°45.628′E)
Bakkhali Island	Bijoybati (Kalisthan 1) (21°35.110′N, 088°17.102′E) Kalisthan (21°35.413′N, 088°17.153′E) Bakkhali (21°35.028′N, 088°17.665′E)
Sagar Island	Gangasagar Colony (21°38.265′N, 088°04.946′E) Pulbari, Paschimpara (21°51.951′N, 088°07.370′E) Shikarpur (21°48.462′N, 088°10.038′E)

Aegiceras corniculatum (L.) Blanco (family Myrsinaceae) is characterized as a small trees of height up to 6 m and 20 cm in diameter. Leaves of this plant are 4–8 cm × 2–4 cm in size, ovate–oblong. Flowering is in late February to early April. Aluri[20] reported the flowering season as March to May. Flower is almost 15 mm long and 13 mm diameter, small in size, star-shaped, white in colour, number of sepals is five and number of petals is also five with umbel inflorescence. Pollen is white in colour and powdery[20,21].

Aegialitis rotundifolia Roxb. (family Plumbaginaceae) is characterized as a shrub or small tree of height up to 3 m and 20 cm in diameter. Leaves are 2.5–9 cm × 3–9 cm in size, rounded or broadly ovate or sub-orbicular. Flowering season is during late February to early April. Flower is almost 18 mm long and 11 mm diameter, white in colour, five sepals with five lobed calyx[21–24].

Study area

The study was performed in the mangrove ecosystem of Sundarban Biosphere Reserve, South 24 Parganas district, West Bengal, India, to understand the interaction between the plant and flower visitors for cross-pollination. Five islands were selected for the study, namely Gosaba, Satjelia, Bali, Bakkhali and Sagar. Among these, three study areas from each island were selected for further analysis (Table 1, Figure 1). The study areas were selected on the basis of availability and accessibility of the studied plants. Map was constructed using QGIS_3.4 Madeira software[25].

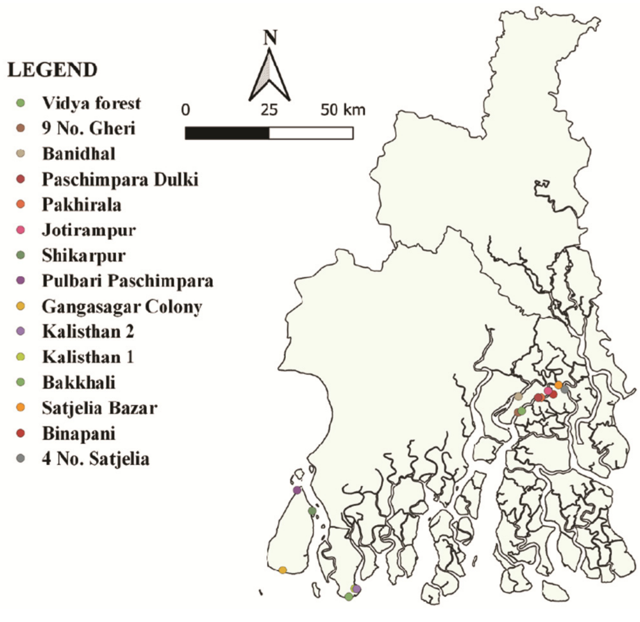

Figure 1. Map of South 24 Parganas, West Bengal, India, including the study areas.

Sampling technique and study period

An area of 500 sq. m (10 m width × 50 m length) was marked from each study area, and from each marked area three individuals of each plant species were selected randomly for analysis. The study was conducted during the flowering to fruiting season of the respective plants during 2016–2018. Each plant individual was monitored for the time period from 6 am to 6 pm with 2 h intervals, thrice in a week. After obtaining the necessary data for the study, the flower visitors of the respective plants were photographed (if possible) and collected with the help of round-headed insect net. Collection was not done for the insects which were identifiable on field. The collection, preservation, setting and pinning procedure was followed according to Jonathan and Kulkarni[26]. For identification of flower visitors, the specimens was taken to the Zoological Survey of India, Kolkata.

Breeding experiment

Breeding experiment was performed to visualize the effect of pollinators on the reproductive success of the studied plants. From each plant individual four branches with maximum number of mature budding conditions were chosen randomly, tagged and among them two branches were bagged. Buds were counted for both conditions in each selected branch and fruits were counted at the end of the experiment for each respective branch. The bagged condition denotes the self or closed pollination system and the unbagged condition denotes the cross- or open pollination system. All the branches studied for the breeding experiment were constantly monitored till the fruit set appeared.

Data collection for foraging efficiency of flower visitors

The flower visitors were continuously monitored for a maximum time of 1 min for the respective plant species. For each observation period, total time spent on flower (TF; time from touching or landing on the flower to departure from the flower by the insect) and total observation time (TT; time spent on a flower and time of flight to the next flower of the same plant species) were taken for the targeted flower visitors with the help of separate stopwatches. The total number of flower visitations during an observation period by an individual of an insect species was also recorded (NF). From these data, two parameters for the estimation of foraging efficiency were analysed: (i) Visitation rate (VR) – average number of flowers visited by an insect per unit of time (NF/TT); in the present study data for VR were analysed in 1 min for each individual of an insect species. (ii) Handling time (HT) – average time spent on a single flower by an insect (TF/NF)[27,28].

Data collection for correlation analysis

To analyse the relationship between insect visitors and bloomed flowers, a correlation analysis was performed. The number of total visitors was counted in 1 min along with the number of bloomed flowers on a single branch of the respective plant selected randomly. A total of 30 observations were taken for each plant species for this analysis. Correlation graph was plotted using Microcal Origin (version 6.0) software and Microsoft Excel 2007 software. A value (r) close to 1 indicates the stronger relationship between the insect visitors and the bloomed flowers of the plant.

Pollen collection procedure and analysis of pollen carrying capacity

To study the pollen loading capacity, the insects were captured during the time period from 8 am to 12 pm from the respective plants, then pollen grains were separated from the body of the insect visitors by smooth brushing and washing. For honeybees, the pollen load of corbiculae was separated prior to the brushing or washing. Only the loose pollen grains attached to different body parts of the insect were taken for estimation. The average value of pollen carrying capacity of each insect was measured to understand its pollination efficiency.

Statistical analysis

Cluster analysis was performed using paired group algorithm (UPGMA) and Jaccard similarity measure, on the basis of presence and absence of insect flower visitors among the studied plant. Similarity and distance index (S&D index) was also measured using Jaccard similarity measure, where 1 indicates the highest similarity and 0 indicates no similarity. Box plot was used for proper profiling of the range of VR and HT among insect visitors in the studied plants. In each one-way ANOVA, 30 observations from each category were selected randomly and divided into 3 groups (10 observations each). The analysis was performed with average value of each group. The value of ANOVA was tested at 5% significance level ($P < 0.05$). All statistical analysis was performed using the PAST software (version-3.19)[29].

Results and discussion

Self and cross-pollination in the breeding system

The breeding mechanism of plants is related to pollinator attraction, where the self-pollinating plant species are less

Table 2. Breeding experiment analysis of four mangroves

Plants	Close pollination (bagged; %)	Open pollination (unbagged; %)
Aegiceras corniculatum (AC)	43.2	50.4
Aegialitis rotundifolia (AR)	39.2	64.1
Avicennia officinalis (AO)	22.9	63.8
Avicennia marina (AM)	19.6	59.6

capable of interaction with the pollinators than the cross-pollinated plants[12,30]. In this study, each of the studied plant species is compatible for both kinds of pollination, but reproductive success is better in cross-pollination. In case of success rate of cross-pollination, AR was associated with the highest percentage of fruit set (64.1), whereas AC with the lowest. However, in the context of self-pollination success, AC was leading with the highest percentage of fruit set (43.2). Both plants from the genus *Avicennia*, because of protandrous condition, were inclined to cross-pollination than self-pollination (Table 2). Pandit and Choudhury[12] reported that AC supports the morphology for self-pollination, which may lead them to be self-fertilized and less dependable to the cross-pollination, but they also reported a great variety of insect flower visitors from this plant. However, the present study showed a slightly higher range of cross-pollination in these plants than self-pollinated fruit set. Coupland *et al.*[31] demonstrated that for pollination of AM, pollen vectors are of greater importance. They also indicated that fruit set of AM is preferably resource-limited. Solomon Raju *et al.*[32] also noted that both AO and AM have the ability to self-pollinate, but they also emphasized the functional role of insect pollinators for these plants. The self-compatibility in the pollination system of AR was also highlighted[24]. In the context of AR pollination system, these plants also reflect the self-compatibility, but cross-pollination increases the fruit set.

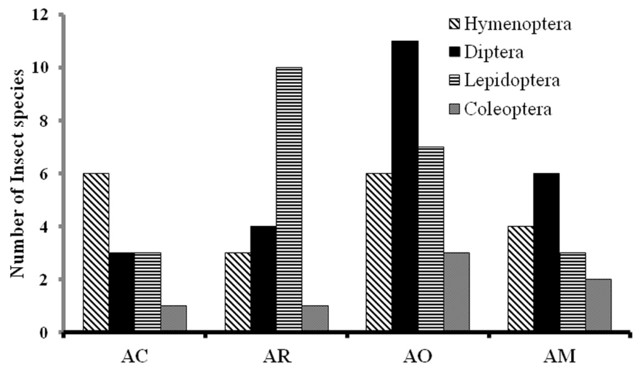

Figure 2. Bar graph of the insect flower visitor species from the studied mangrove plants.

Diversity of insect flower visitors of mangroves

A total of 38 insect species from four orders were recorded as visitors from the studied plants. Among them, order Diptera holds the highest position with 14 species, followed by Lepidoptera and Hymenoptera with 12 and 9 species respectively. Coleoptera was included with the lowest number of species, viz. only three. The highest number of species was reported from AO (27 species), whereas AC was related to only 13 species. The dipterans and coleopterans were strongly related to both *Avicennia* plant species while lepidopterans were mostly dominant in AR. In case of hymenopetrans insects, both AO and AC showed higher number of species compared to others (Table 3, Figure 2).

The present study focuses on the five common flower visitors of these plants, viz. *Apis dorsata*, *Apis mellifera*, *Chrysomya megacephala*, *Danaus chrysippus* and *Micraspis discolor*. Among them, the most abundant insect flower visitor in these four plants was *M. discolor* and the honey-bee species. As *A. mellifera* is commonly domesticated in the Sundarbans in the form of apiculture, therefore closer to the apiculture zone the abundance of this species (*A. mellifera*) was more compared to the wild honey-bee species *A. dorsata.* The abundance of *M. discolor* was comparatively higher almost among all the studied mangrove plants throughout the study areas. The abundance of *C. megacephala* and *D. chrysippus* was moderate among the four plants. In case of *C. megacephala*, the abundance was least in AR, whereas *D. chrysippus* was mostly encountered in these plant species. There was no significant variation related to insect visitor abundance among each of the plants during three years of study (AC: $F_{2,6} = 0.927$, *P*-value – 0.44; AR: $F_{2,6} = 0.2.49$; *P*-value – 0.16; AO: $F_{2,6} = 0.563$; *P*-value – 0.59; AM: $F_{2,6} = 0.25$, *P*-value – 0.77).

Analysis of similarity in species composition

Regarding flower visitor species composition among the four plants, similarity and distance analysis (Jaccard cluster analysis) indicates that AO and AM have the highest similarity (44%). Though these two plants differ slightly in blooming time, they bear similar type of floral morphology and therefore insects of the same type serve these plants as flower visitors/pollinators[6,32]. AC and

Table 3. Flower-visitor insects from four mangrove plants

Order	Species	AC	AR	AO	AM
Hymenoptera	*Apis* (*Megapis*) *dorsata dorsata***	+	+	+	+
Hymenoptera	*Apis mellifera***	+	+	+	+
Hymenoptera	*Oreumenoides edwardsii*	+	–	–	–
Hymenoptera	*Campsomeriella* (*C.*) *collaris collaris*	–	–	–	+
Hymenoptera	*Scolia* (*Discolia*) *affinis*	+	–	+	–
Hymenoptera	*Subancistrocerus sichelii*	–	–	+	–
Hymenoptera	*Xylocopa fenestrate*	–	–	+	+
Hymenoptera	*Delta conoideum*	+	–	+	–
Hymeoptera	*Sceliphron* sp.	+	+	–	–
Diptera	*Chrysomya megacephala***	+	+	+	+
Diptera	*Allobaccha amphithoe*	+	–	+	+
Diptera	*Physiphora aenea*	–	–	+	+
Diptera	*Musca* (*Musca*) *domestica*	+	–	–	+
Diptera	*Eristalis arvorum*	–	–	+	+
Diptera	*Sarcophaga dux*	–	–	+	–
Diptera	*Sarcophaga* (*Iranihindia*) *martellata*	–	–	+	–
Diptera	*Tabnus striatus*	–	–	+	–
Diptera	*Eristalinus polychromatus*	–	–	+	–
Diptera	*Chrysops dispar*	–	+	+	+
Diptera	*Tinda indica*	–	–	+	–
Diptera	*Cadrema pallida* var. *bilineata*	–	–	+	–
Diptera	*Dideopsis aegrota*	–	+	–	–
Diptera	*Bactrocera cucurbitae*	–	+	–	–
Lepidoptera	*Euploea core*	+	+	+	–
Lepidoptera	*Danaus chrysippus***	+	+	+	+
Lepidoptera	*Tirumala limniace*	–	+	+	+
Lepidoptera	*Catopsilia pyranthe*	–	+	+	+
Lepidoptera	*Junonia almana*	–	+	+	–
Lepidoptera	*Catochrysops strabo*	–	+	–	–
Lepidoptera	*Cepora nerissa*	–	+	–	–
Lepidoptera	*Danaus melanippus*	–	+	–	–
Lepidoptera	*Hypolimnas bolina*	+	+	–	–
Lepidoptera	*Papilio demoleus*	–	+	–	–
Lepidoptera	*Euchrysops cnejus*	–	–	+	–
Lepidoptera	*Melanitis leda*	–	–	+	–
Coleoptera	*Micraspis discolor***	+	+	+	+
Coleoptera	*Cicindela* (*Callytron*) *limosa*	–	–	+	–
Coleoptera	*Adoretus lacustris*	–	–	+	+

**Denotes common visitor among the four plants.

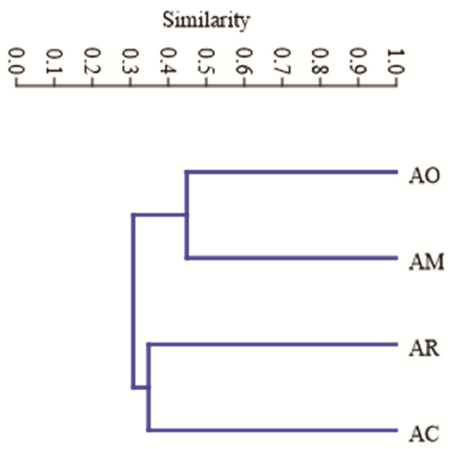

Figure 3. Cluster analysis, Jaccard similarity measure with UPGMA method for four mangrove plants on the basis of their species composition. Here 1 indicates the maximum similarity and 0 indicates no similarity.

AR hold the next position with 34% similarity in species composition (Figure 3).

Correlation analysis between bloomed flowers and visitor abundance

The relation between bloomed flowers and visitor abundance is important for pollination. In this study, each plant shared a strong positive relation with the insect visitors. Among the four mangroves, AC had the strongest relation with insect visitor abundance ($r = 0.80$, $n = 30$, $P < 0.05$). Both AO and AM, showed similar kind of relation with the visitors ($r = 0.737$, $n = 30$, $P < 0.05$ for AO, and $r = 0.736$, $n = 30$, $P < 0.05$ for AM). However, AR showed comparatively weaker relationship with insect abundance ($r = 0.71$, $n = 30$, $P < 0.05$; Figure 4).

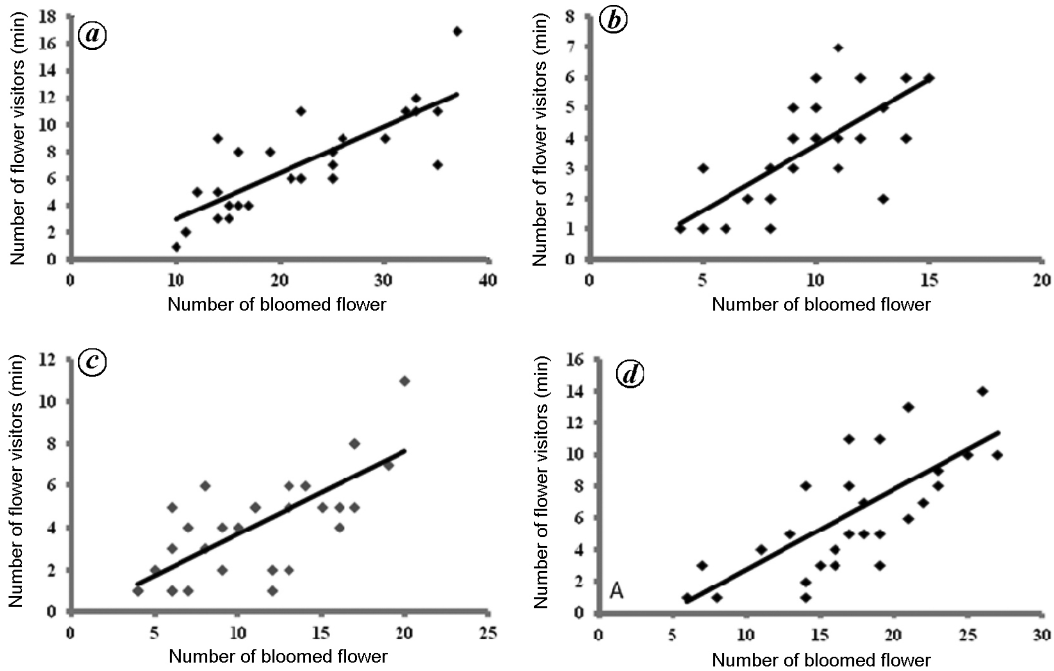

Figure 4. Correlation analysis (r) between the number of visitors/min and the number of bloomed flowers in each of the four studied mangrove plants: ***a***, *Aegiceras corniculatum*; ***b***, *Aegialitis rotundifolia*; ***c***, *Avicennia officinalis*; ***d***, *Avicennia marina*. Here $n = 30$ (n is the total number of observations). Values closer to 1 indicate the highest correlation and 0 indicates the lowest correlation.

Effect of visitation rate and handling time in foraging efficiency of flower visitors/pollinators

In the plant–pollinator system, VR and HT of the pollinating insect play an important role in reproductive success in relation to cross-pollinated angiosperms[33]. Ne'eman *et al.*[34] described visitation frequency as an important component for pollinator performance in plant reproduction.

In the present study, in the context of highest VR among the four plants, *A. dorsata* and *A. mellifera* were reported in AC (12.8 ± 0.70 and 11 ± 0.75 flowers/min respectively), *C. megacephala* showed the highest VR in AO (7.3 ± 0.59 flowers/min), *D. chrysippus*, the lepidopteran visitor was associated with AR (5.1 ± 0.32 flowers/min) and *M. discolor* (2.8 ± 0.29 flowers/min) was related to AM (Figure 5). Thus, AC, AO and AM showed a significant difference in VR among their four flower visitors, viz. *A. dorsata*, *A. mellifera*, *C. megacephala* and *D. chrysippus*, but no significant difference was recorded in VR among the flower visitors of AR. *M. discolor* was excluded from the analysis because of its low VR among all the plants (Table 4). Based on VR analysis of insect visitors among the four plants, each of the flower visitors except *M. discolor* showed significant difference among the four plants (Table 5). VR of pollinators may vary on the basis of different parameters like flower structure, design, colour, size and nectar production. Insect visitation may also vary due to spatial and temporal arrangement in floral display. Due to these reasons, different flower visitors respond differently in their activity with respect to a single plant[35]. In this study, each insect-specific analysis denotes that VR for a single insect significantly differs among the four plants, except *M. discolor*. The information on VR of these flower visitors/pollinators will help in conservation and management procedures aiming at adequate pollination of these mangrove plants.

Furthermore, it is crucial to monitor HT by a visitor to understand the foraging behaviour. Among the five common flower visitors, HT of *M. discolor* was the highest for all four mangrove plants (Figure 6). In case of plant-specific analysis, significant difference was noted in HT among the remaining four flower visitors, viz. *A. dorsata*, *A. mellifera*, *C. megacephala* and *D. chrysippus* in each of the studied plants. *M. discolor* was excluded from this analysis because of its high HT throughout the study period (Table 4). In case of visitor-specific analysis, only *A. mellifera* showed significant variation in HT among the four plants (Table 5).

Different responses of flower visitors among the plants may occur due to the difference among pollination resources and plant morphology. This study demonstrates that though VR was higher in AC for both honeybee species, they spent more time on the flower of AR. Due to the morning anthesis and odourless flowers, pollination occurs during daytime for flowers of the AR plant. In the nectar of this plant, some non-essential and essential amino acids such as lysine, phenylalanine, threonine,

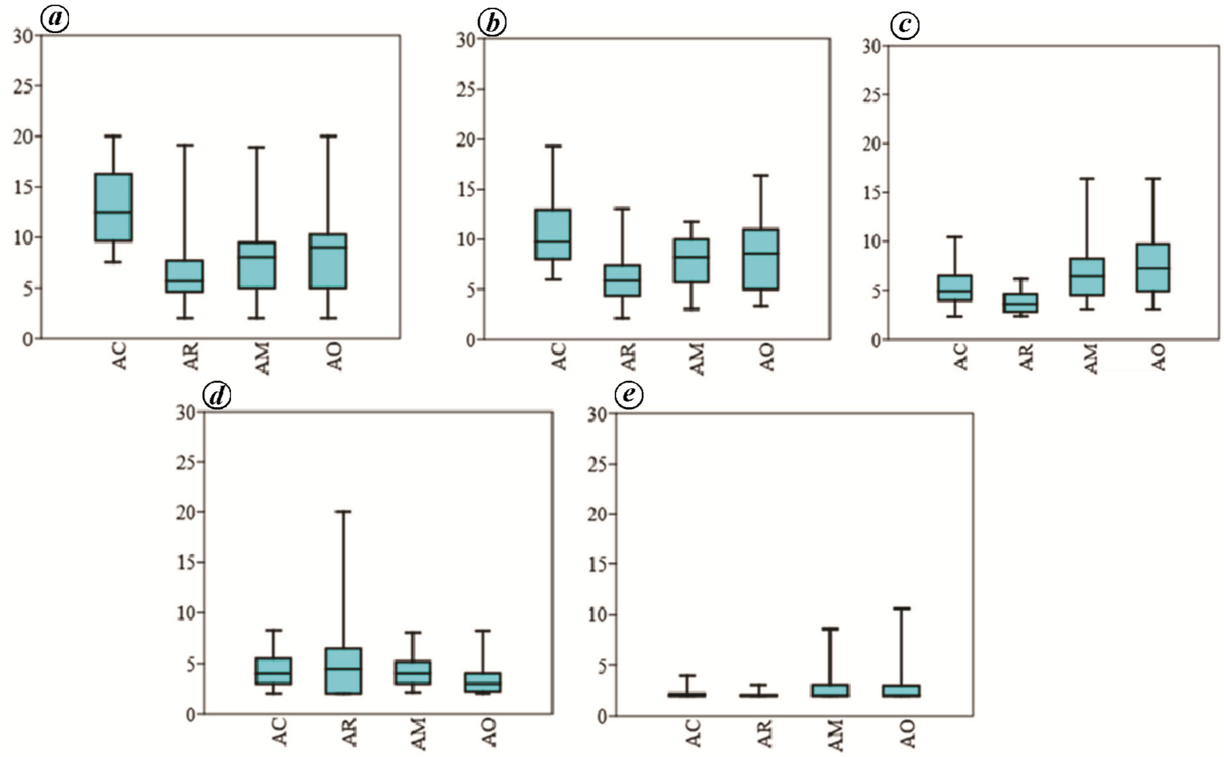

Figure 5. Box plot analysis for visitation rate (VR) of five insect flower visitors among four mangrove plants: ***a***, *Apis dorsata*; ***b***, *Apis mellifera*; ***c***, *Chrysomya megacephala*; ***d***, *Danaus chrysippus*; ***e***, *Micraspis discolor*.

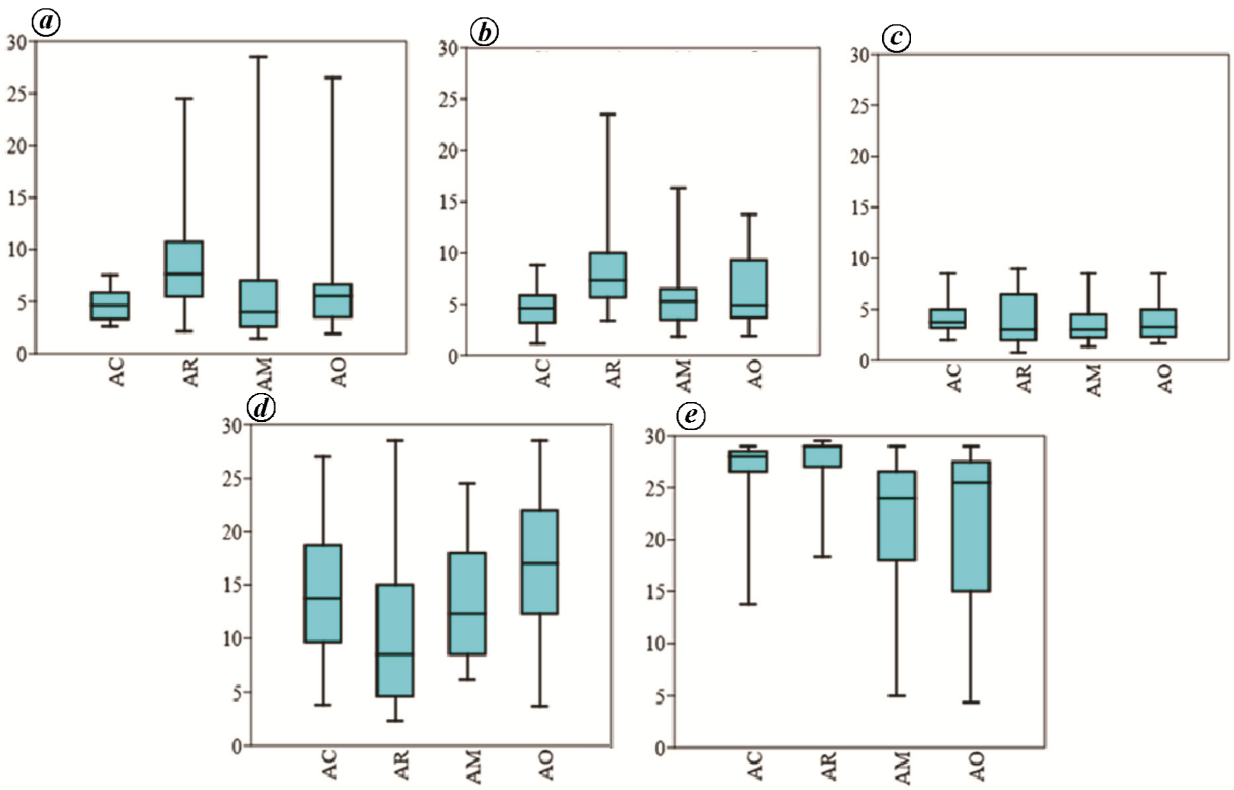

Figure 6. Box plot analysis for handling time (HT) of five insect flower visitors among four mangrove plants: ***a***, *A. dorsata*; ***b***, *A. mellifera*; ***c***, *C. megacephala*; ***d***, *D. chrysippus*; ***e***, *M. discolor*.

Table 4. One-way ANOVA of plant-specific visitation rate (VR) and handling time (HT) among different insect flower visitors

	Sum of squares	d*f*	Mean square	*F*-value	$P < 0.05$
Visitation rate					
AL					
Between groups	158.66	3	52.88	28.95**	0.00012
Within groups	14.61	8	1.82		
Total	173.27	11			
AR					
Between groups	11.65	3	3.88	3.15	0.08
Within groups	9.85	8	1.23		
Total	21.51	11			
AO					
Between groups	52.47	3	17.49	23.31**	0.0002
Within groups	6.00	8	0.75		
Total	58.48	11			
AM					
Between groups	30.04	3	10.01	4.28**	0.04
Within groups	18.69	8	2.33		
Total	48.74	11			
Handling time					
AC					
Between groups	227.28	3	75.76	44.72**	0.00002
Within groups	13.55	8	1.69		
Total	240.83	11			
AR					
Between groups	71.43	3	23.81	4.94**	0.03
Within groups	38.54	8	4.81		
Total	109.98	11			
AO					
Between groups	281.94	3	93.98	24.34**	0.0002
Within groups	30.08	8	3.86		
Total	312.83	11			
AM					
Between groups	154.63	3	51.54	7.34**	0.01
Within groups	56.14	8	7.01		
Total	210.78	11			

The analysis includes VR and HT of four flower visitors × a single plant. **Significant at $P < 0.05$.

tryptophan, valine and histidine are present and honey bees require some of them. Therefore, these plants may be better adapted for bee pollination, or they show better melittophilous pollination[24,36]. Though the AR plants are reported as bee-pollinated, the present study shows that the activity of lepidopteran insects, specially butterflies was also high (Table 3). *D. chrysippus* showed the highest VR for this plant. However, dipteran insect activity was very low compared to insects of other orders in this plant. The present study showed that in the two *Avicennia* plant species (AO and AM), activity of dipteran insect was comparatively higher than the other two plants. The butterfly provided highest HT on AO among the four plants. With the context of previously reviewed literatures, fly pollination is more favourable for both the *Avicennia* species because of their floral morphology. The nectar containing amino acids plays an important role in the interaction between insect and flower[12,23]. Probably hexose-rich nectar of AM may attract the dipteran flower visitors, whereas wasp and butterfly are adaptive to sucrose content of nectar. Among ten essential amino acids that the insects require, arginine, lysine, threonine and histidine are present in the AO plant. Proline and glycine are also present in the nectar of AO plant; and proline stimulates the salt receptor cells in flies[32]. Due to the floral structure, AC plant is compatible with self-pollination, but the present study shows a slightly higher reproductive success in cross-pollination for this plant. Easily accessible resources, i.e. pollen grains and nectar of this plant contribute to a wide range of visitors.

Table 5. One-way ANOVA of insect flower visitors on their plant-wise VR and HT

	Sum of squares	d*f*	Mean square	*F*-value	*P* < 0.05
Handling time					
Apis dorsata					
Between groups	25.94	3	8.64	1.26	0.35
Within groups	54.91	8	6.86		
Total	80.86	11			
Apis mellifera					
Between groups	26.79	3	8.93	5.22**	0.02
Within groups	13.66	8	1.70		
Total	40.46	11			
Chrysomya megacephala					
Between groups	0.2387	3	0.07	0.05	0.982
Within groups	11.767	8	1.47		
Total	12.005	11			
Danaus chrysippus					
Between groups	56.30	3	18.76	2.425	0.14
Within groups	61.92	8	7.74		
Total	118.23	11			
Micraspis discolor					
Between groups	93.61	3	31.20	1.98	0.19
Within groups	125.92	8	15.74		
Total	219.53	11			
Visitation rate					
Apis dorsata					
Between groups	66.20	3	22.06	5.13**	0.02
Within groups	34.39	8	4.29		
Total	100.60	11			
Apis mellifera					
Between groups	40.80	3	13.60	17.81**	0.0006
Within groups	6.10	8	0.76		
Total	46.90	11			
Chrysomya megacephala					
Between groups	22.35	3	7.45	11.31**	0.0030
Within groups	5.27	8	0.65		
Total	27.62	11			
Danaus chrysippus					
Between groups	4.98	3	1.66	3.932**	0.053
Within groups	3.38	8	0.42		
Total	8.37	11			
Micraspis discolor					
Between groups	1.10	3	0.36	1.69	0.24
Within groups	1.74	8	0.21		
Total	2.84	11			

The analysis includes VR and HT of a single flower visitor × four plants. **Significant at $P < 0.05$.

Pollination efficiency in relation to pollen carrying capacity

Pollen carrying capacity of flower visitors is one of the most important factors affecting the plant reproductive success for cross-pollinating plants. Among the five common flower visitors, *A. dorsata* had the ability to carry the highest amount of pollen among all insects in all the plants. While *M. discolor* was found to carry the least amount of pollen for AC, AM and AO plants, whereas for AR plant *C. megacephala* was observed to carry the least amount of pollen (Table 6).

M. discolor has been reported as a potential biological control agent because of its predatory activity[37,38]. Various coccinellids species have been reported as pollen feeders, and the adult *M. discolor* was also found to feed on pollen and prey species[39]. The present study reveals that *M. discolor* has the highest HT and the lowest VR among all the other studied insects. This may be because of its predation or pollen-feeding efficiency. It carries a

Table 6. Pollen carrying capacity of flower visitors to the studied plants (mean ± SE; *n* = 10 for *Apis dorsata* and *Apis mellifera* and *Chrysomya megacephala* and *Danaus chrysippus*; *n* = 5)

Insect species	AC	AR	AM	AO
A. dorsata	479.6 ± 76.9	584.1 ± 79.0	295.8 ± 38.7	377.5 ± 47.5
A. mellifera	399.0 ± 51.2	477.6 ± 53.9	212.4 ± 23.1	255.7 ± 33.7
C. megacephala	219.1 ± 30.2	87.2 ± 9.0	202.7 ± 26.2	107 ± 17.9
D. chrysippus	113.8 ± 7.7	157.4 ± 21.0	77.6 ± 20.0	103.8 ± 19.5
M. discolor	97.1 ± 13.2	104.6 ± 12.9	59.5 ± 9.0	71.1 ± 7.0

n, Number of individuals studied.

low amount of pollen, mostly on the ventral side of the body. *M. discolor* may have the lowest pollination efficiency among the five common flower visitors. Among honeybees, *A. dorsata* and *A. mellifera* were reported to carry a large amount of pollen from each plant, but *A. dorsata* was found to carry the highest amount among all insects (Table 6). The dipteran and lepidopteran insects, e.g. *C. megacephala* and *D. chrysippus* both carried moderate amount pollen from each of the plants, whereas in the context of pollen-carrying capacity, *C. megacephala* carried the lowest amount of pollen for AR plant and *D. chrysippus* carried the lowest pollen for AM plant. *C. megacephala* carried the highest amount pollen for AM plant, and *D. chrysippus* carried the highest amount of pollen for AR plant (Table 6). Therefore, with respect to quantity of average pollen grains carried by an insect, *A. dorsata* holds the highest position followed by *A. mellifera* for all the plants.

Conclusion

The five common flower visitors, viz. *A. dorsata*, *A. mellifera*, *C. megacephala*, *D. chrysippus* and *M. discolor* aid in cross-pollination success in all the four mangrove plants (AO, AM, AC and AR) studied here. Both *A. dorsata* and *A. mellifera* pollinate the four plant species in an efficient manner. Chakrabarty[17] reported that bees show greater preference for hive towards *Avicennia* species. *C. megacephala* and *D. chrysippus* are moderately efficient for the plants. Though *M. discolor* is included with the lowest pollen carrying capacity, its functional role in terms of predation and transferring pollen may help the plants in relation to protection and reproductive success.

Various conservation approaches have been used throughout the world for conserving insect pollinators. In Australia, *C. megacephala* has been conserved in the process of rearing for use as a pollinator of mango plants[40]. *A. mellifera* is also reared in apiculture in different parts of the Indian Sundarbans. The proper protection of habitats of insects may help in the conservation of essential insect diversity for this ecosystem. Mangrove is considered as a threatened ecosystem all over the world[1]. The Sundarbans mangrove forest is also exposed to various natural catastrophes like cyclone, tsunami, heavy rainfall and other anthropogenic threats[14]. It has been reported that seven common mangroves of the Sundarbans are threatened and need to be conserved; AC is one of them and AR is a near threatened species[16]. Therefore, it is essential to protect and conserve the mangroves and flower visitor species because conservation of these insect species is necessary for long-term conservation of this unique mangrove ecosystem.

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