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Research Article

Diversity, Abundance, and Foraging Behaviour of Insect Pollinators in Litchi (*Litchi chinensis* Sonn.) under Hot and Subhumid Conditions

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Insect pollinators and flowering plants have a long-standing, coevolutionary, mutualistic relationship. One such example is the litchi tree (*Litchi chinensis* Sonn.), a fruit crop that relies on insect pollination. Litchi flowers are hermaphroditic, but they cannot self-pollinate due to self-sterility, unlike self-pollinating plants. Therefore, insect pollinators are crucial to successful fruit development. To understand the pollinator's foraging behaviour and diversity associated with litchi under hot and subhumid conditions, the present study was conducted on the Shahi variety of litchi at the ICAR-Research Complex for Eastern Region, Farming System Research Centre for Hill and Plateau, Ranchi (Jharkhand), India. During the flowering period, a total of 19 species of insect pollinators from the orders Hymenoptera, Diptera, Lepidoptera, and Coleoptera were observed visiting litchi inflorescences. *Apis mellifera* and *Apis dorsata* were the most dominant pollinator species. Each species displayed distinct characteristics in terms of abundance and diversity. Varied foraging speeds (stay times) were also noted, with *A. dorsata* (6.94 s) being the fastest and *Musca domestica* (2.88 s) being the slowest. Pollinator activity was highest in the eastern direction, between 8:00 a.m. and 10:00 a.m. *Apis florea* had the highest foraging rate (visitation rate) (14.02 flowers visited per minute), followed by *Apis mellifera*, while *Episyrphus taeniops* had the lowest. *Apis* species were identified as the most abundant and frequent visitors in litchi orchards.

1. Introduction

Litchi (*Litchi chinensis* Sonn.), in the family Sapindaceae, is a highly valued perennial fruit crop in India. It holds great potential as an income source for small and marginal farmers, particularly in Bihar and Jharkhand states of India [1]. In the eastern region of India, the process of flower bud differentiation in litchi typically begins in December and concludes by the end of January [2]. Flower panicles emerge in January and extend until the end of February. Each inflorescence usually contains three distinct types of flowers [1]. These include Type I male flowers (M1), Type II flowers (functioning as female but hermaphrodite in nature), and Type III flowers (pseudohermaphroditic, also functioning as male) [1]. Despite having both functional male and female flowers on the same tree, self-pollination does not occur in litchi due to the self-sterility of hermaphrodite flowers [1]. The self-sterility of hermaphrodite flowers in litchi leads to complete dependence on insect pollinators (anthophilous species) for a successful fruit set [3–6]. The plant species that are most in need of pollinator services, such as litchi, have typically evolved to rely on a small number of anthophilous species to reproduce successfully [5].

Litchi flowers attract a large number of insects, especially bees, because of the availability of nectar, primarily during the morning hours [3, 5]. Literature shows that litchi attracts

a wide range of insects as pollinators [1, 3, 5, 7, 8]. Abrol [3] has documented a total of 29 insect species from 22 genera, 12 families, and 6 orders as pollinators of litchi blooms. Among these insect species, *Apis dorsata* Fabricius, 1793; *Apis mellifera* Linnaeus, 1758; *Apis cerana* Fabricius, 1793; and *Apis florea* Fabricius, 1787, are the most common flower visitors, accounting for more than 65 percent of all recorded insect species [3, 5]. The activity, diversity, and foraging behaviour of pollinators may differ according to weather, space, location, and time [6, 9, 10, 11]. Even though the pollinator's diversity and abundance are not indicators of efficient pollinators because pollinators may be there only for robbing of the nectar from flowers without touching the stigma [12]. Diversity and abundance of insects are the parameters of pollinator success in cross-pollinated crops [13]. Numerous studies have explored the diversity and abundance of honey bee pollination in litchi crops worldwide as well as in India [3, 5, 7, 8, 14], yet there are limited spatiotemporal foraging behaviour studies that demonstrate the pollination efficiency in litchi. Therefore, it is essential to identify location-specific pollinators to conserve and manage the most effective pollinators. The present study was conducted in hot and humid climates of the eastern plateau and hilly regions of India to understand the diversity, abundance, and foraging activity of flower visitors in litchi.

2. Materials and Methods

2.1. Study Site and Experimental Design. The experiments described in this study were carried out in the orchards of the Shahi variety of litchi established in the National Germplasm Repository of Subtropical Fruit Crops at the ICAR Research Complex for Eastern Region, Farming System Research Centre for Hill and Plateau Region (FSRCHPR), Palandu, Ranchi, in the year 2022 (23° 45′ N, 85° 30′ E, elevation 620 m above msl). The litchi trees are planted within a one-hectare area at a 10×10 m distance from row to row and plant to plant. The trees in the orchard are approximately 25 to 30 years old, indicating their physiological maturity.

2.2. Floral Biology of Litchi Cultivars. In this study, various litchi phenological stages and flowering parameters were observed using a standardised *Biologische Bundesantalt*, *Bundessortenamt*, and *Chemische Industrie* (BBCH) scales, as described by Wei et al. [15]. This scale describes the growth stages of the litchi plant using a three-digit numerical system including 7 principal growth stages viz., bud (0), leaf (1), shoot development (3), inflorescence emergence (5), flowering (6), fruit development (7), and fruit maturity (8). Observations were made from the initiation of the first flower opening stage (610) until the shedding of M2 flowers in the Shahi cultivar of litchi. Observations methodology was employed according to Srivastava et al. [5] from three randomly chosen trees. From each selected tree, ten panicles were tagged for accurate counting. Visual counting of fully matured panicles (stage 509) was performed to determine the number of flowers. To calculate the flowering duration, the number of days from the first flower opening to fruit set (hermaphrodite female) and shedding (pseudohermaphrodite male) of the tagged flowers on the same selected plants was recorded. In addition, the male, female, and hermaphrodite female flower ratio was determined from randomly tagged panicles.

2.3. Floral Visitor Census. In this study, observations on insect pollinators were conducted starting from their initial appearance on the litchi inflorescences until fruit set, which were determined at the BBCH scale 617 stage when 90% of the flowers had faded. The sight count technique was employed for observations [5, 8]. To further identify the observed insect species, sweep net techniques were used to collect specimens. The collected specimens were systematically pinned and sent to the Division of Entomology at the Indian Agricultural Research Institute (IARI) in New Delhi for taxonomic identification. This process of collection and identification was carried out throughout the entire data collection during litchi flower opening to fruit set (BBCH scale 610 to 617). Daily observations were made at two-hour intervals, starting at 8:00 a.m. and concluding at 2:00 p.m.

2.4. Foraging Behaviour. Foraging speed or stay time was defined as the time spent by an insect visitor on a flower, measured in seconds. The number of flowers visited by insect visitors per minute was defined as a foraging rate or visitation rate [16, 17]. To measure the foraging speed/rate, an Android mobile phone equipped with a stopwatch feature was utilized. The stopwatch was activated when the insect visitor landed on a flower and stopped when it departed. These timings were recorded at four different time periods: 07:30–09:30 a.m., 09:30–11:30 a.m., 11:30 am–01:30 p.m., and 01:30–03:30 p.m.

2.5. Relative Abundance and Diversity of Pollinators. For the observation phase, a total of 10 trees from the Shahi cultivar were randomly selected [5]. From each tree, one inflorescence was chosen from each direction, resulting in a total of four inflorescences per tree. Selected inflorescences were used to count the floral visitors. To analyze the diversity and abundance of the observed floral visitors, various indices were employed. The methodologies for calculating these indices were standardised by Cottom and Curtis [18], Margalef [19], Shannon and Weiner [20], Pielou [21], and Simpson [22].

2.5.1. Species Richness (S). Species richness (S) is defined as the number of species observed in a direction or defined habitat.

2.5.2. The Simplest Index. The Simplest Index of species diversity was determined based on total species (S) numbers and the total number of individual pollinator species (N) in a given direction.

2.5.3. Margalef Richness Index. Margalef's Richness Index was calculated by using the formula proposed by Margalef [19]:

$$\text{Da} := \frac{(S-1)}{\log_e N}, \tag{1}$$

where Da is Margalef's Richness Index, S is the total number of species, and N is the total number of individuals of all pollinator species.

2.5.4. Shannon–Wiener Diversity Index (H^1). This index was calculated based on the formula proposed by Shannon and Weiner [20]:

$$H^1 = -\sum_{i=1}^{s} N_i \ln N_i, \tag{2}$$

where N_i is the proportion of individuals of all pollinator species.

2.5.5. Species Evenness Index (E). The Species Evenness Index was calculated as per the formula suggested by Pielou [21]:

$$E = \frac{H^1}{\ln N}. \tag{3}$$

2.5.6. Species Dominance Index (D). This index was calculated as per the formula proposed by Simpson [22]:

$$D = \sum \left(\frac{s}{N}\right)^2. \tag{4}$$

All the indices were analyzed using Excel and Past 4.03 software [23].

3. Results

3.1. Floral Biology of Shahi Cultivar of Litchi. During the study period, panicle initiation was observed between March 10 and March 30, 2022. The first phase, known as the male phase, lasted for approximately 4.50 ± 0.22 days (Table 1). The second phase, which is the hermaphrodite phase, overlapped slightly with the first phase. The duration of the second phase varied from 6.50 ± 0.27 days, and the last phase, the pseudo-hermaphrodite phase, typically started one to two days before or just after the completion of the second phase. The total flowering duration in litchi ranged from 18.50 ± 0.45 days.

The percent composition of male and female flowers was recorded and presented in Table 1. Type-I (M1) was reported with a composition of 45.75%, signifying its percentage in the total composition. Similarly, for Type-II (F), the composition was stated as 16.73%. Lastly, Type-III (M2) has a composition of 37.51%.

3.2. Diversity of Floral Visitors. During the observation period, the field conditions were favourable for insect-pollinating activities in the litchi orchards. Temperature ranges from a minimum of 13.02°C to a maximum of 38.64°C with a relative humidity of 45–50%. The litchi flowers attract a total of 19 insect species from four orders and ten families of the class Insecta (Table 2). The order Hymenoptera had the highest representation, with six species from three families: Apidae, Halictidae, and Vespidae. Among these, the Apidae family was the most abundant, with four honey bee species: *A. mellifera*, *A. dorsata*, *A. cerana*, and *A. florea* (Figure 1). The order Diptera was the second most dominant, with six species from three families, Syrphidae, Muscidae, and Calliphoridae, observed visiting the litchi flowers. Three distinct species, *Episyrphus balteatus*, *Eristalinus* sp., and *Copestylum mexicanum*, represented the family Syrphidae, which includes hoverflies (Figure 2). The other two families each had a single species of insect visitor. In addition, we observed six species from the order Lepidoptera (Figure 1), belonging to the families Pieridae, Nymphalidae, and Erebidae, as floral visitors. We observed only one species from the order Coleoptera, specifically the ladybird beetle *Ortalia horni* from the Coccinellidae family, on the litchi flowers. Among the other insect visitors and pollinators observed in the present study, various species were recorded, including *Eumenes* sp., *Halictus* sp., *E. taeniops M. domestica, L. sericata, Calliphora* sp., *P. brassicae, E. core, N. jumbah, N. lacticinia, T. hamata*, and *H. bolina*.

Table 1: Characteristics of Shahi litchi flowering phenology.

Types of flowers	Duration (days)	Composition (%)
Type-I (M_1)	$4.50^{b} \pm 0.22$	45.75
Type-II (F)	$6.50^{ab} \pm 0.27$	16.73
Type-III (M_2)	$7.50^{a} \pm 0.22$	37.51

Type-I = staminate flowers; Type-II = hermaphrodite female flowers; Type-III = hermaphrodite male flowers. For type-I (45.75) and type-III (37.51) falls in one group so we can make non-sig with letter "a," and type-II (16.73) significantly differ from group a so we can make them as "b."

Observation of pollinator species composition showed that *A. mellifera* was the predominant species, comprising 47 percent of the total pollinators (Figure 3). Subsequently, *A. dorsata* accounted for 19 percent, *M. domestica* for 7 percent, and *A. cerana, A. florea*, and *E. balteatus* each contributed 5 percent. Other insect species collectively accounted for the remaining 12 percent of pollinators.

3.3. Abundance and Diversity of Pollinators. Examining the pollinator population and flowering phenological data revealed that the mid-flowering period saw the highest pollinator population, which then gradually declined in the following days. The total number of recorded species varied between 18 and 19 in different directions and 15 to 19 at different times (Table 3(a, b)). The Shannon–Wiener Diversity Index (H') was the highest in the east direction (1.89) and the lowest in the north direction (1.67), while there were no comparative differences observed in terms of time. Margalef's Richness Index (Da) values ranged from 2.37 to 2.47 in all directions and from 2.10 to 2.41 during the day. The dominance index revealed that the north and west directions had higher dominance, while the east and south directions had lower dominance. Certain species showed higher dominance at 8:00 a.m. and 10:00 a.m., while the least dominancy among species occurred at 12:00 p.m. and 2:00 p.m.

Table 2: Insect taxa visiting litchi flowering and their role during the study.

Common name	Scientific name	Family	Role
Italian bee	*Apis mellifera* Linnaeus	Apidae	Pollinator
Rock bee	*Apis dorsata* Fabricius		Pollinator
Indian bee	*Apis cerana* Fabricius		Pollinator
Little bee	*Apis florea* Fabricius		Pollinator
Wasp	*Eumenes* sp. Latreille	Vespidae	Flower visitor
Sweat bee	*Halictus* sp. Latreille	Halictidae	Pollinator
Cabbage butterfly	*Pieris brassicae* Fabricius	Pieridae	Flower visitor
Common crow	*Euploea core* Fabricius	Nymphalidae	Flower visitor
Blue moon butterfly	*Hypolimnas bolina* Linnaeus		Flower visitor
Chestnut-streaked sailor	*Neptis jumbah* Moore		Flower visitor
Dark tiger butterfly	*Tirumala hamata* MacLeay		Flower visitor
Common nyctemera	*Nyctemera lacticinia* Grote	Erebidae	Flower visitor
Housefly	*Musca domestica* Linnaeus	Muscidae	Pollinator
Blowfly	*Lucilia sericata* Meigen	Calliphoridae	Flower visitor
Blue bottle fly	*Calliphora* sp. Robineau-Desvoidy		Flower visitor
Hoverfly	*Eristalinus taeniops* Wiedemann	Syrphidae	Pollinator
Hoverfly	*Episyrphus balteatus* De Geer		Pollinator
Hoverfly	*Copestylum mexicanum* Macquart		Pollinator
Ladybird beetle	*Ortalia horni* Weise	Coccinellidae	Flower visitor and partial pollinator

3.4. Foraging Speed of Pollinators. The present study examined the foraging speed of pollinators and found that *A. dorsata* had the highest foraging speed (6.94 seconds), followed by *A. mellifera* (5.27 seconds), and *Musca* sp. had the lowest foraging speed (2.88 seconds) (Figure 4). Between 9:30 a.m. and 11:30 a.m., all pollinator species showed the highest foraging activity, while between 1:30 p.m. and 3:30 p.m., they showed the least activity. We documented the count of pollinators visiting a flower within a specific time frame and found that *A. florea* had the highest visiting frequency (14.02 flowers visited/min), followed by *A. mellifera*, and *E. taeniops* had the lowest. Moreover, all species demonstrated their maximum foraging speeds around 9:00 a.m., while their minimum foraging speeds were observed at 3:00 p.m.

4. Discussion

The present study results suggest that the litchi flowering pattern and pollinator abundance, diversity, and foraging behaviour vary in time and space. Litchi flowering panicles begin in the eastern part of India in the first to the second week of February, while in the northern parts, they begin in the second week of February [1, 2, 24]. The timing of panicle initiation in the present study differs from earlier reported periods. Genetic, environmental, and demographic factors influence both the timing and pattern of flower initiation in litchi [1, 25, 26]. In addition, litchi flowering initiation is dependent on temperature requirements, categorising cultivars as either having low chilling requirements or high chilling requirements [25]. Panicles have a significant difference in the type of flower across various cultivars of litchi [26]. Similarly, the phases of male, female, and hermaphrodite flower initiation also vary depending on environmental, genetic, and demographic factors [25]. Litchi typically has a first phase, known as the male phase, and a second phase, which is the hermaphrodite phase, which overlaps slightly with the first phase. The second phase and the last phase, the pseudohermaphrodite phase, typically begin one to two days before or just after the second phase is completed [25]. The observed flowering duration in the present study is well within the ranges reported, from 13 ± 4 days in China to 30 ± 3 days in Piazi [27].

The observed environmental conditions during the study period were optimum for litchi flowering [1]. We found a rich diversity and abundance of insect species visiting litchi flowers [14]. Litchi flowers are good sources of nectar and pollen [5]. These reported insect species primarily gathered nectar and pollen from the litchi flowers. While we observed these insects on the flowers, their effectiveness as pollinators may vary. Chaudhary et al. [7], Abrol [3], Srivastava et al. [5], and Rai et al. [8] showed the role of flower visitors and pollinators in their studies on litchi. They also observed a range of insect visitors and confirmed that these insects predominantly gathered nectar from the litchi flowers and played an important role as pollinators. Pollinator species composition showed that *A. mellifera* was the predominant species, comprising 47 percent of the total pollinators [3]. Kumar et al. [28] reported that 12 insect species from the orders Hymenoptera and Diptera visited litchi blossoms throughout the flowering period. Srivastava et al. [5] observed 20 pollinator species from the orders Diptera, Hymenoptera, and Coleoptera visiting litchi blossoms in Muzaffarpur, Bihar. According to Abrol [3], the honey bee species *A. dorsata*, *A. mellifera*, *A. cerana*, and *A. florea* were the most prevalent and effective pollinators of litchi blossoms, accounting for over 65 percent of all pollinating insects. Abrol [3] and Kumar et al. [28] found that hymenopterans, specifically bees, were the most prevalent group of insect pollinators on litchi, accounting for 74.69%

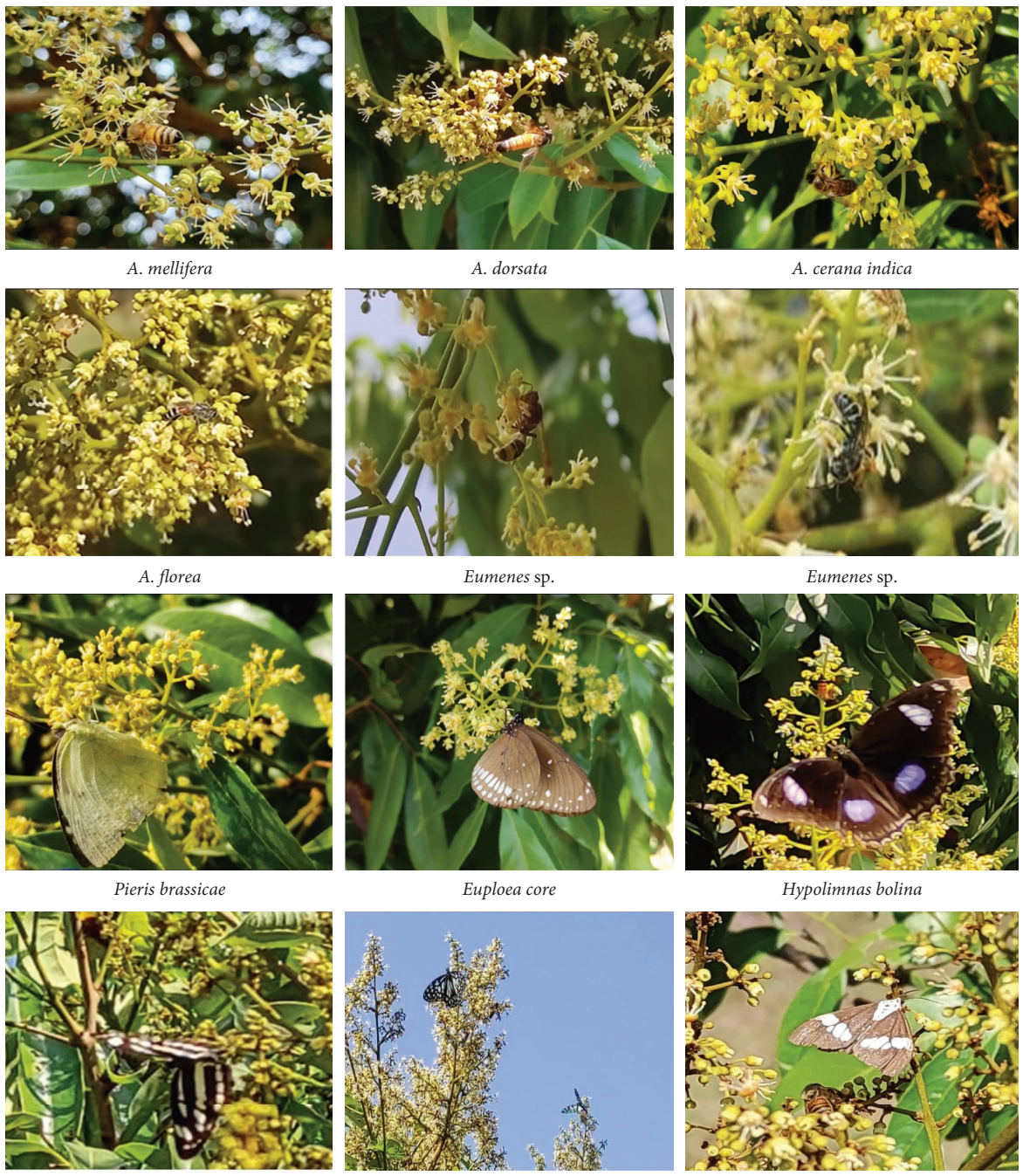


Figure 1: Important hymenopteran/lepidopteran species visiting/pollinating on Shahi variety of litchi.

of all pollinators. We assigned the remaining pollinators to other insect species. Bees from the Apidae family predominantly visited Sesamum plants (69.4%), with Halictidae (10.6%) and Megachilidae (7.1%) following closely behind [29]. Similarly, Srivastava et al. [5] reported that 74.69% of the insect visitors to litchi flowers were hymenopterans, with other insect species representing the remaining 25.21%. Rai and Srivastav [30] identified *A. dorsata*, *A. mellifera*, and *A. cerana indica* as significant and effective pollinators of litchi in the Bihar region.

The Shannon–Wiener Diversity Index (H') was the highest in the east direction and the lowest in the north direction, while there were no significant differences observed in terms of time. The evenness value indicated that pollinators were equally distributed, with dominant species including *A. mellifera, A. dorsata, A. cerana, A. florea, M. domestica, E. taeniops*, and *E. balteatus*. The Dominance Index revealed that the north and west directions had a higher dominance, whereas the east and south directions had a lower dominance. Similar to the present study, the

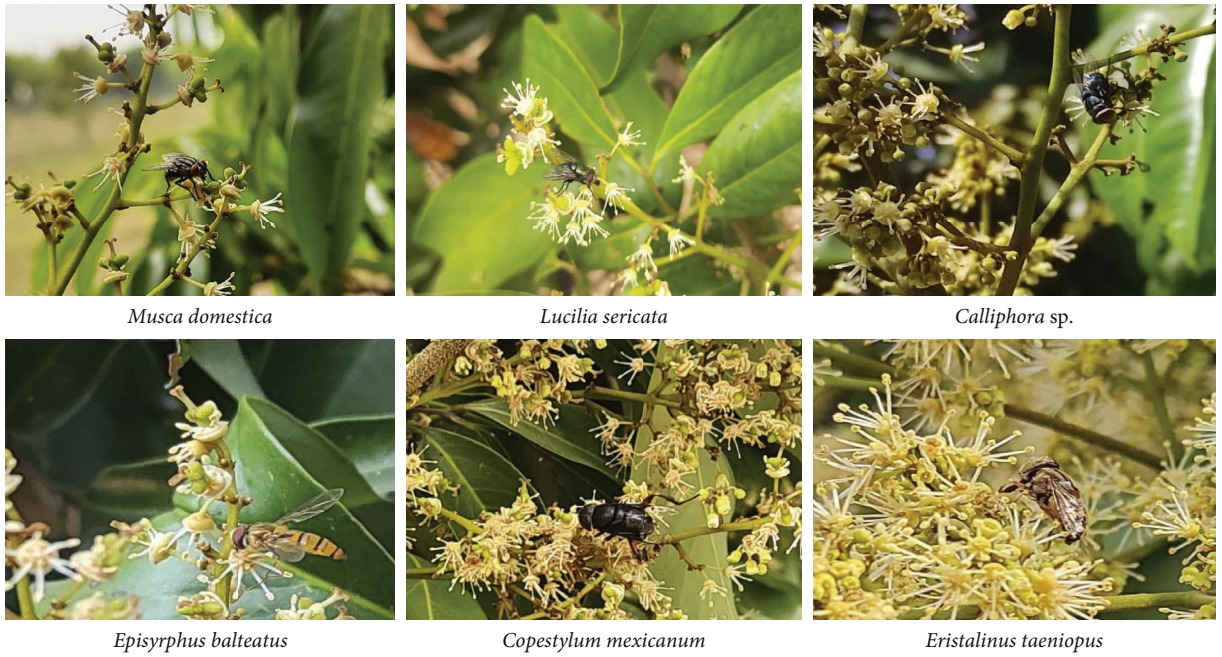


Figure 2: Important dipteran species visiting/pollinating on Shahi variety of litchi.

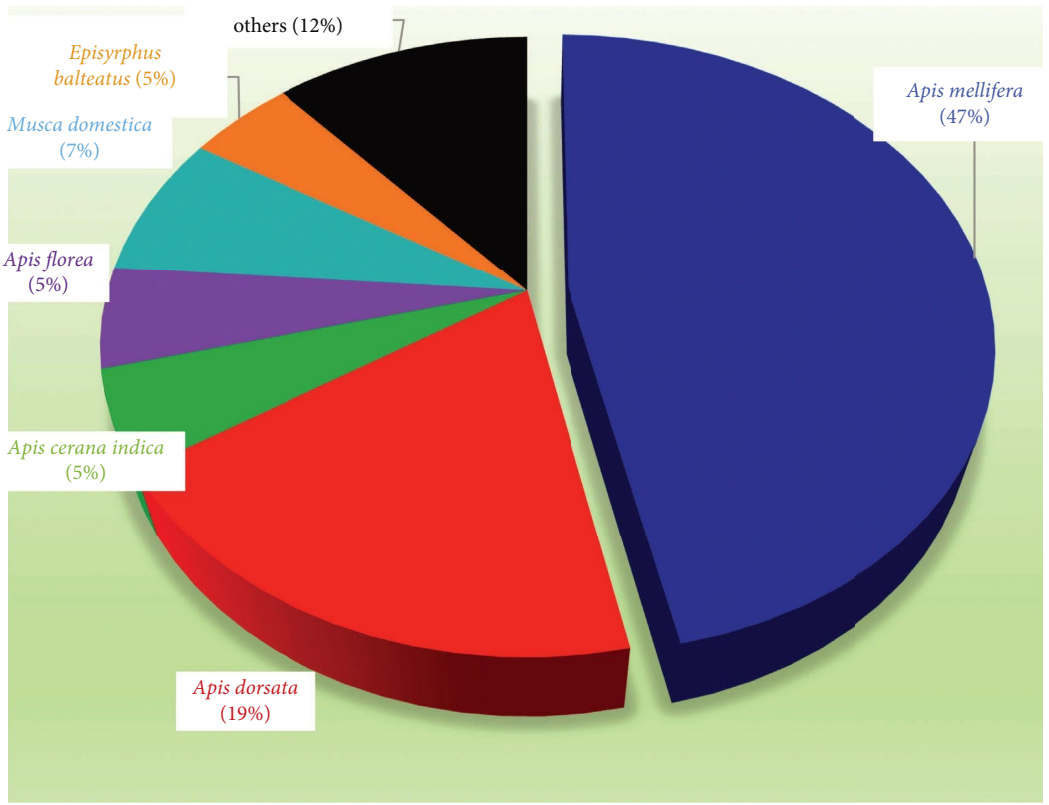


Figure 3: Relative composition of pollinators visited on Shahi variety of litchi.

number of bee foragers per minute per panicle peaked between 10:30 a.m. and 11:30 a.m., followed by 11:30 a.m. and 12:30 p.m., and a smaller peak was observed at 3:30 p.m. and 4:30 p.m. in the litchi orchards of Bihar [31]. Shiwani and Karnatak [32] also observed that bees spent the most time on litchi flowers in the morning, specifically between 9:00 a.m. and 11:00 a.m. Rai et al. [8] also reported that pollinator activity on litchi blossoms initiated in March, with a peak in

Table 3: (a) Temporal diversity indices of pollinators on the Shahi variety of litchi at the time of flowering. (b) Spatial diversity indices of pollinators on the Shahi variety of litchi at the time of flowering.

(a)

Diversity indices (time (T))	A	S	H'	Da	D
08:00 a.m.	2311	19	1.75	2.32	0.29
10:00 a.m.	1763	19	1.80	2.41	0.27
12:00 p.m.	1301	18	1.79	2.37	0.27
02:00 p.m.	896	15	1.75	2.10	0.26

(b)

Diversity indices (direction)	A	S	H'	Da	D
East	1820	19	1.89	2.40	0.24
West	1468	19	1.74	2.47	0.29
North	1308	18	1.67	2.37	0.30
South	1675	19	1.81	2.43	0.27

A = abundance, S = numbers of species, H' = Shannon–Wiener Diversity Index, Da = Margalef's Richness Index, and D = Dominance Index.

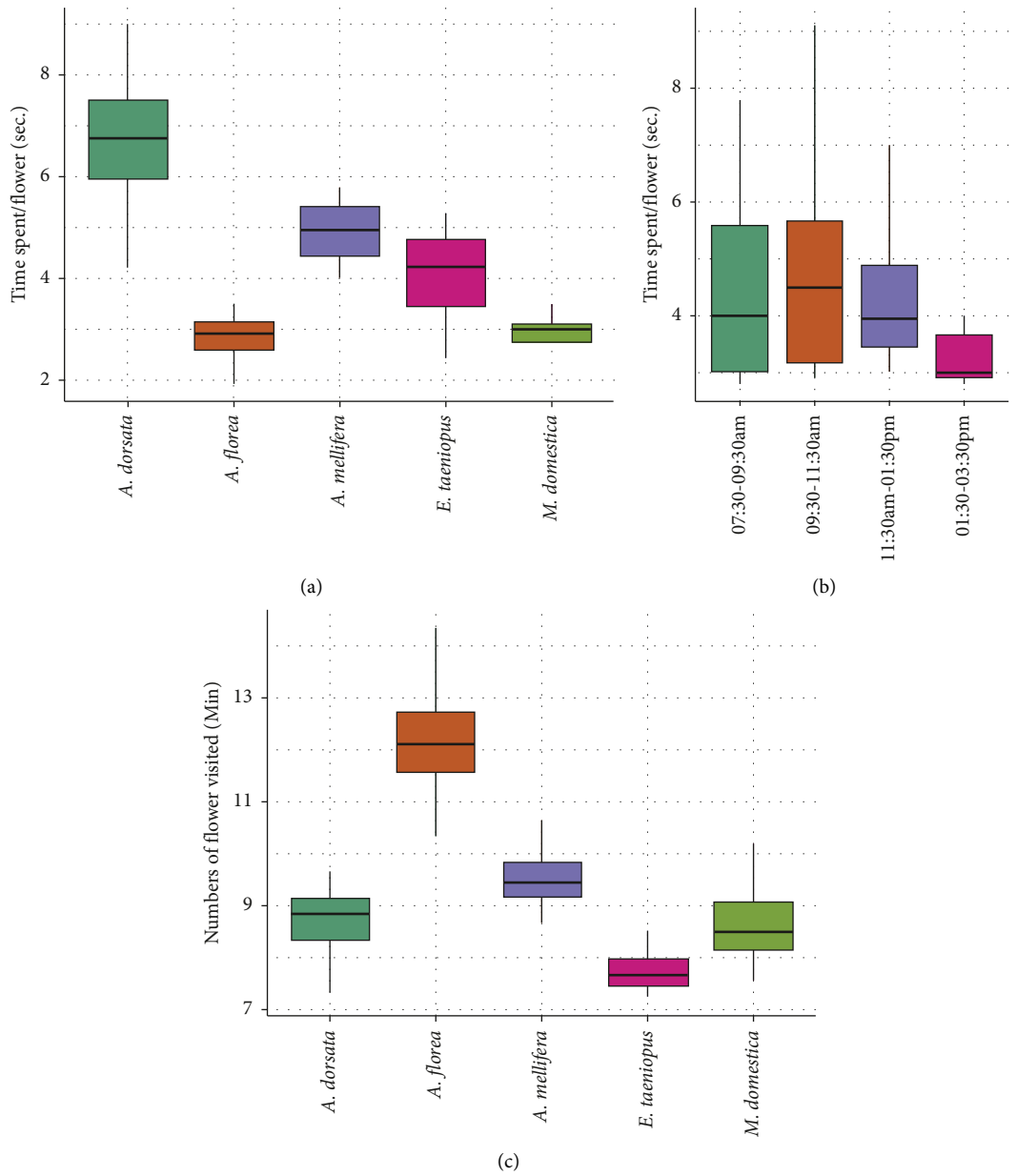


Figure 4: Foraging behaviour: (a) foraging speed with respect to pollinator species; (b) foraging speed with respect to day hours; (c) visitation frequency of different pollinators on Shahi variety of litchi.

the eastward direction around mid-March. Therefore, they found that mid-March and eastward orientations were favourable for insect pollinators in litchi trees.

The foraging speed of pollinators was maximum in *A. dorsata* followed by *A. mellifera* and was minimum for *Musca* species. The body weight of honey bees, a significant factor influencing foraging activity, may contribute to the variations in foraging rates [17]. The count of pollinators visiting a flower within a specific time frame was documented, revealing that *A. florea* had the highest visiting frequency followed by *A. mellifera*, while *E. taeniops* had the lowest. The visitation frequency seems to be directly correlated to the amount of time handling a single flower (handling time not studied in the present study) [33]. In the present study, it may be that *A. florea* spends little handling time per flower, so visitation frequency may be more relative to others. The foraging speed of pollinators is similar to results reported by Chaudhary et al. [7], who determined foraging rates of 2.71 seconds, 3.40 seconds, and 5.06 seconds per panicle for *A. cerana, A. mellifera*, and *A. dorsata*, respectively. Mishra and Kumar [17] found that *A. dorsata* had the fastest foraging speed (10.28 seconds), followed by *A. mellifera* (9.15 seconds), while *A. florea* exhibited the slowest foraging speed (6.97 seconds). Moreover, all three species demonstrated their maximum foraging speeds around 9:00 a.m., while their minimum foraging speeds were observed at 3:00 p.m. The quality and quantity of pollen and nectar, the spraying of agrochemicals, temperature, humidity, wind speed, and rainfall all influence the foraging speed and behaviour of pollinators [16, 34].

5. Conclusion

The flower biology of the Shahi cultivar of litchi in the region uncovered key insights and was influenced by genetic and environmental factors. The fact that there are three stages of flowering and that the male, female, and male hermaphrodite flowers are all different shows how the availability of nectar, pollen, physiological factors, and environmental conditions can cause pollinators' composition differences. We found a rich diversity and abundance of insect species visiting litchi flowers according to time and direction. These comprehensive findings provide valuable insights into the complex dynamics of litchi floral biology, pollinator abundance, diversity, and behaviour in litchi orchards.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

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