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Research Article
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Bees in Litchi Bloom: Assessing the Diversity and Foraging Behaviour of Bee Visitors in a Litchi Ecosystem

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ABSTRACT

A study, conducted during the litchi blooming period of 2022 and 2023, provided valuable insights into the diversity and foraging behaviour of bee visitors associated with litchi flowering in the sub-Himalayan Terai region of West Bengal. The study enlisted 15 species of bees from 5 families, namely Andrenidae (1 species), Apidae (7), Colletidae (1), Halictidae (4), and Megachilidae (2), visiting the litchi bloom. Among them, Apidae family alone contributed 49.56% of the total bee assemblage. As an individual species, *Apis mellifera* was the most frequent visitor (1.09 individuals/m^2/minute). In contrast, *Megachile laticeps* was the least abundant (0.28 individuals/m^2/minute) visitor with least foraging speed (2.20 seconds) and highest foraging rate (13.96 flowers/minute/forager). A good diversity of bees was ensured by the higher values of Shannon diversity (2.672) and Margalef richness (2.385) indices. Furthermore, higher value of Sheldon evenness (0.965) and lower value of Simpson dominance (0.071) indices confirmed no prominent dominance of a single/few species in the assemblage. Weather parameters like T_{max}, RH_{min}, BSH, and wind speed had significant ($p<0.05$) effects on the foraging parameters. Maximum foraging activity of different bee visitors was recorded at 10:00-12:30 hours. Thus, by understanding these dynamics, it may be possible to develop targeted strategies to conserve and support these vital pollinators and ensure sustainable litchi production in the region.

Keywords: Ecological indices, forager abundance, foraging rate, foraging speed, weather factors.

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INTRODUCTION

Pollination is that valuable ecosystem service that safeguards the existence of human life on earth by ensuring the availability of food. Pollination service links the agro- and natural-ecosystems with the wild and human life cycle (Potts et al., 2016; Garibaldi et al., 2022) and maintains the natural balance of the ecosystems thereby. This service is the backbone of our food production and uplifts the socio-economic condition by enhancing the food quality and quantity (Saha, Munshi, & Laskar, 2023). About 87% of plant species from all over the world depend on animal pollinators (insects, mammals, birds, etc.), and this dependency may reach ~94% in tropical areas (Ollerton, Winfree, & Tarrant, 2011; Pires & Maués, 2020). Among different animal pollinator groups, bees (Hymenoptera: Apiformes) form the most efficient group (Danforth, 2007), as they are responsible for pollinating ~80% of the world's flowering plants (Michener, 2007), contributing to ~30% of the world's total food production (de Figueiredo-Mecca, Bego, & do Nascimento, 2013). Moreover, if it is a cross-pollinated crop, the role of bee pollination becomes more crucial for the reproduction and food production of the crop.

Litchi (*Litchi chinensis* Sonn.), a perennial fruit crop under the Sapindaceae family, is a cross-pollinated plant species, exhibiting a significant reliance on various bee pollinators. This cross-pollination of litchi is due to its typical flowering pattern. Usually, a litchi plant has panicles, each bearing 3,000 flowers, of which just 200 get pollinated, providing only 5–60 mature fruits (Lal, Gupta, Marboh, Kumar, & Nath, 2021a). Each panicle has three types of flowers that open in a sequence as follows: the type-I, which is essentially a male flower with 6–8 stamens, devoid of any ovule; the type-II, which is a hermaphrodite functional female flower with fully developed pistil and stigma, as well as 5–8 stamens that do not dehisce; and the type-III, which is a pseudo-hermaphrodite male with 6–8 stamens, producing plenty of viable pollen and also possessing rudimentary pistils that are devoid of style and stigma (Stern & Gazit, 1996). Despite the presence of both functional male and female flowers on the same plant, the self-sterile nature of these hermaphrodite flowers and short period of stigma receptivity restrict self-pollination, leading to complete dependency on insect pollinators to ensure proper fruit setting (Lal et al., 2021b; Nath, Saha, Laskar, & Debnath, 2023). In addition, litchi flowers produce a profuse amount of quality nectar and pollen (Wu et al., 2017; Xiao et al., 2023), which are major requirements for different insect pollinators, specifically bees, and attract a number of bee species thereby.

In the Indian context, litchi is a highly valued fruit crop, as India holds the 2nd rank in global litchi production, after China. This crop exhibits significant potential as a source of income for resource-poor communities (Rathore et al., 2014). Specifically, for the small and marginal farmers of eastern states of India, like Bihar, Jharkhand, and West Bengal, this crop has contributed enormously to their socio-economic upliftment. The sub-Himalayan Terai region of West Bengal is also a part of it. In these eastern states, litchi used to bloom in the spring months, i.e., March-April (Malhotra, Singh, & Nath, 2018), and is visited by a number of insect pollinators. In this respect, diversity, abundance, and visitation rate of insect pollinators are certain key parameters that determine the success of pollination in cross-pollinated crops (Mitchell, Flanagan, Brown, Waser, & Karron, 2009). A wide range of studies have already been conducted to determine the diversity and abundance of varying insect pollinators, more specifically the bees, in litchi flowers from different corners of India (Abrol, 2006; Srivastava, Sharma, Pandey, Anal, & Nath, 2017; Das, Jha, & Halder, 2019; Kumari, Rana, Bhargava, & Reddy, 2023; Kumari, Choudhary, Dey, & Dhakar, 2024), but with limited spatiotemporal foraging attribute studies of bees on litchi bloom. Furthermore, different agro-ecological regions possess unique species composition, and the foraging behaviour of these species differs with the environmental conditions of that region (Schleimer & Frantz, 2025). Therefore, identifying native pollinators and assessing their foraging behaviour is critical for conserving and managing them effectively in order to achieve sustainable crop production. That's why, in light of the facts stated above, the present study has been conducted in the perhumid sub-Himalayan Terai region of West Bengal to investigate the diversity of bee pollinators and understand their foraging behaviour in the litchi bloom. This could offer crucial insights into the interactions between litchi bloom and bees, emphasizing the role of specific pollinators to enhance the fruit set and yield of litchi in the region.

MATERIAL AND METHODS

Study area

The observations were recorded in the litchi orchard of Uttar Banga Krishi Viswavidyalaya (UBKV), Pundibari, West Bengal, India (coordinates: 26.39610° N; 89.38640° E; altitude: 43 m.a.s.l.), during the spring (March-April) of 2022 and 2023, the usual time period for litchi blooming in this region. During this period, this area is characterized by a good floral diversity, including different field crops, vegetables, ornamental plants, and natural vegetation, like different trees and weed flora, ensuring an ample environment for different bee pollinators.

This region has a unique perhumid climate (Nath, Saha, Pokhrel, & Laskar, 2024). During the study period, the region had a modest temperature range of 14.8–35.5°C and a daily rainfall range of 0–44.6 mm, creating an optimal condition for litchi flowering and fruiting, as well as for different bees to have a good foraging efficiency.

Collection, preservation, and identification of bee pollinators

To observe the diversity, representatives of different bee species visiting litchi flowers were collected during the active foraging period of the day using a sweeping insect net. Field photographs of bees on litchi flowers were captured using a Nikon D5600 digital camera attached with a 300mm lens. The collected specimens were preserved in sample vials containing 70% ethanol and were carried back to the laboratory for identification. In the laboratory, the specimens were stretched, pinned, dried, and observed under a Nikon SMZ25 stereo-zoom microscope attached to a Nikon DS-Ri2 microscope camera. Proper identification keys and corresponding literatures (van der Vecht, 1952; Michener, 2007; Pauly, 2009; Ascher, Risch, Soh, Lee, & Soh, 2016; Nidup & Dorji, 2016; Falswal, Akoijam, Haorongbam, & Dey, 2022) were used to identify the specimens up to family, generic, subgeneric, and species level. Vouchered specimens were preserved in the laboratory for future reference.

Recording of observations

Observations on different foraging attributes (forager abundance, foraging rate, and speed) of different bee visitors were recorded for four weeks (D1–D4) (i.e., 09.03.2022 [D1], 16.03.2022 [D2], 24.03.2022 [D1], 01.04.2022 [D4], 12.03.2023 [D1], 19.03.2023 [D3], 26.03.2023 [D3], and 03.04.2023 [D4]), usually starting from the 2nd week of March till the flowers remain, at a weekly interval. Data was recorded at four time intervals (i.e., 07:30-10:00 [T1], 10:00-12:30 [T2], 12:30-15:00 [T3], and 15:00-17:30 hours, respectively) of the respective dates. For each bee species, five replications (one replication from one plant) were performed at the specified dates and times.

These findings on different foraging attributes are significant due to their contribution in determining the pollination behaviour and efficiency of different bee pollinators in litchi flowers. The abundance was recorded as the number of individuals of a specific bee species visiting 1 m^2 of floral area per minute. For this purpose, five 1 m^2 areas (one area from one plant) with efficient blooming were selected and pre-fixed by tying threads on branches. To record the foraging rate, the number of flowers visited by an individual of a specific bee species in one minute was noted using a stopwatch and hand tally meter. The foraging speed was recorded as the time spent by an individual forager (in seconds) on each flower by eye estimation using a stopwatch. It is essential to note that several bee species with analogous physical characteristics could not be distinguished under field conditions, and that's why they were considered as a single type.

Diversity indices

Based on the abundance data, we have calculated the following (Table 1) ecological indices for species diversity, evenness, richness, and dominance at different times and different observational weeks during both years.

Table 1. Different ecological indices for species diversity, richness, evenness, and dominance used in the study

Indices	Equation	Indications	References
Shannon diversity index (H')	$-\sum_{i}^{n} p_i ln p_i$	pi = proportion of species in a community (ni/N)	Shannon, 1948
Margalef richness index (Da)	$\frac{S-1}{ln N}$	S = total number of species; N = total number of individuals	Margalef, 1958
Sheldon evenness index (E)	$\frac{e^{H'}}{S}$	H' = Shannon diversity; S = total number of species	Sheldon, 1969
Simpson dominance index (D)	$\sum p_i^2$	pi = proportion of species in a community (ni/N)	Simpson, 1949

Recording weather data

Data on different weather factors such as maximum and minimum temperature (T_{max}/T_{min}), maximum and minimum relative humidity (RH_{max}/RH_{min}), rainfall, bright sunshine hours (BSH), evaporation (EVP), and wind speed were recorded from the Meteorological Unit, located at the UBKV farm, within 500m from the experimental site.

Statistical analysis

Data on abundance and foraging rate were normalized using the square root transformation. Three-factor factorial ANOVA followed by Duncan's new multiple range test (DNMRT) (at α = 0.05 level) was performed for foraging parameters considering bee species, observational weeks, and times as the factors. Moreover, for foraging rate and speed, the analyses were missing plot three-factor factorial ANOVA in order to eliminate the bias due to the absence of a bee species at any particular week or time (to eliminate the bias due to '0' value). The effect of various weather factors on the cumulative bee abundance in the litchi flower was performed using Pearson's correlation. All these statistical analyses were performed in RStudio®, version 4.4.1 (R Core Team, 2024), except the chord network that was prepared using Origin® software in order to visualize the abundance of different bee pollinators during both years.

RESULTS

Assessment of bee diversity

Our study documented 15 species of bee visitors across 9 genera belonging to 5 families (Table 2) associated with litchi bloom in the region under consideration. Of them, 5 species could be identified only up to their generic level. Among these families, Apidae had the highest number of representative species (7 species), whereas Andrenidae and Colletidae had only one representative in the bee assemblage. This bee assemblage was composed of 3 species of honey bees, and the remaining were solitary bees. Field photographs of different bee species visiting litchi flowers have been presented in Fig. 1.

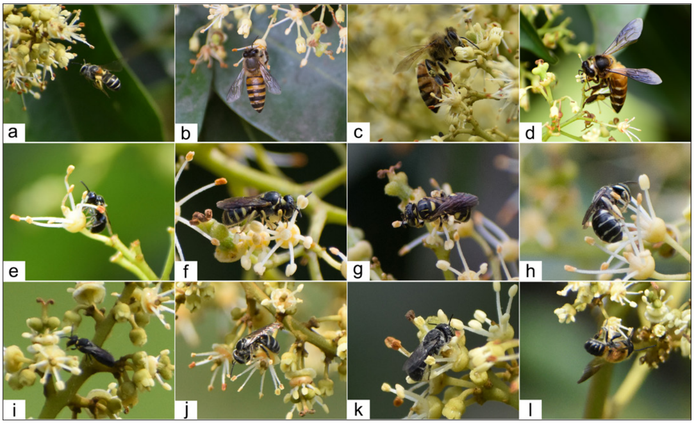

Figure 1. Field photographs of different bee visitors on litchi bloom. (a) *Andrena* sp.; (b) *Apis cerana*; (c) *Apis mellifera*; (d) *Apis dorsata*; (e) *Braunsapis* sp.; (f) *Ceratina cognata*; (g) *Ceratina compacta*; (h) *Ceratina lieftincki*; (i) *Hylaeus floralis*; (j) *Lasioglossum cavernifrons*; (k) *Heriades* sp.; (l) *Megachile laticeps*.

Table 2. Associated bee visitors in litchi flowering in the region under consideration.

Denoted as	Family	Species name	Materials examined	Figures
Sp1	Andrenidae	*Andrena* sp.	6♀	Fig. 1(a)
Sp2	Apidae	*Apis* (*Apis*) *cerana* Fabricius, 1793	6♀	Fig. 1(b)
Sp3		*Apis* (*Apis*) *mellifera* Linnaeus, 1758	7♀	Fig. 1(c)
Sp4		*Apis* (*Megapis*) *dorsata* Fabricius, 1793	8♀	Fig. 1(d)
Sp5		*Braunsapis* sp.	3♀	Fig. 1(e)
Sp6		*Ceratina* (*Ceratinidia*) nr. *cognata* Smith, 1879	3♂	Fig. 1(f)
Sp7		*Ceratina* (*Ceratinidia*) *compacta* Smith, 1879	2♂, 3♀	Fig. 1(g)
Sp8		*Ceratina* (*Ceratinidia*) *lieftincki* van der Vecht, 1952	2♂, 2♀	Fig. 1(h)
Sp9	Colletidae	*Hylaeus* (*Nesoprosopis*) nr. *floralis* (Smith, 1873)	1♂, 1♀	Fig. 1(i)
Sp10	Halictidae	*Lasioglossum* (*Ctenonomia*) *albescens* (Smith, 1853)*	2♂, 1♂	—
		Lasioglossum (*Ctenonomia*) *cavernifrons* (Blüthgen, 1926)*	1♂, 1♀	Fig. 1(j)
Sp11		*Lasioglossum* sp.	2♂, 1♀	—
Sp12		*Seladonia* sp.	2♀	—
Sp13	Megachilidae	*Heriades* sp.	4♀	Fig. 1(k)
Sp14		*Megachile* (*Aethomegachile*) *laticeps* Smith, 1853	1♂, 2♀	Fig. 1(l)

**Lasioglossum albescens* and *Lasioglossum cavernifrons* exhibit analogous morphological characteristics, rendering differentiation impracticable in field conditions. That's why, data on their foraging behaviour have been aggregated as a single category.

Assessment of forager abundance

Our study revealed no significant difference (p = 0.419) in the bee pollinator abundance between the years, with a marginally higher number of bees encountered in 2022 than in 2023. Among the 5 bee families, Apidae bees have the highest abundance, which was approximately half (49.56%) of the total bee abundance (Fig. 2). Furthermore, honey bees contributed about 24.93% of the total bee assemblage, and the rest were solitary bees.

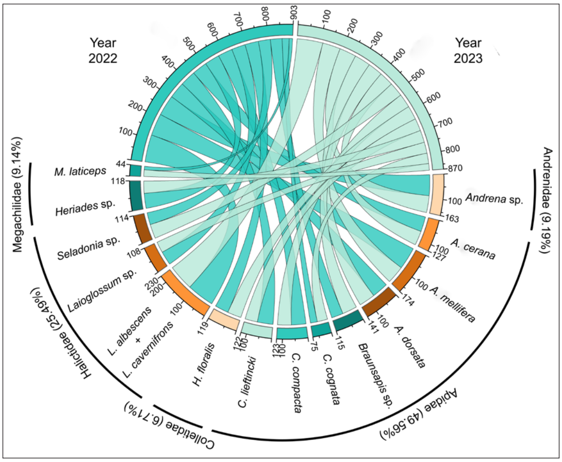

Figure 2. Chord network linking between the yearly abundance with the abundance of different bee visitors from different families

Table 3 (ANOVA) represented a significant difference (p<0.001) in the abundance among different bee species across different observational weeks and times. Abundance was recorded highest for Sp10, which represented two species, i.e., *L. albescens* and *L. cavernifrons* (mean abundance of 1.44 individuals/m^2/minute), followed by Sp3 or *A. mellifera* (mean abundance of 1.09 individuals/m^2/minute). Abundance of *M. laticeps* (Sp14) was extremely low (mean abundance of 0.28 individuals/m^2/minute) as compared to other bee species, and sometimes this species was not even seen to visit litchi bloom in certain observational units. Peak abundance of these bee pollinators was noted at 10:00–12:30 hours (T2) and then decreased gradually, with least abundance noted at evening hours, i.e., 15:00–17:30 time interval (T4). Moreover, it is noteworthy that the abundance of bee pollinators was highest during the first week of observation or flowering (D1) but decreased significantly during later weeks (Table 3).

Table 3. Assessment of abundance (as number of individuals/m^2/minute) of different bee pollinators in litchi bloom at different weeks and times from pooled data of two years using three-factor factorial ANOVA and DNMRT post-hoc test (α=0.05) with n=2240 no. of observations.

Week	Time	Species														Weekly mean
		Sp1	Sp2	Sp3	Sp4	Sp5	Sp6	Sp7	Sp8	Sp9	Sp10*	Sp11	Sp12	Sp13	Sp14	
D1	T1	1.20 (1.26)	0.70 (1.04)	1.30 (1.30)	1.10 (1.23)	0.80 (1.07)	0.50 (0.94)	0.90 (1.14)	0.70 (1.04)	0.70 (1.05)	1.40 (1.34)	0.70 (1.05)	0.50 (0.95)	0.80 (1.09)	0.20 (0.81)	0.94 (1.14)a
	T2	1.30 (1.30)	1.40 (1.31)	1.50 (1.34)	1.40 (1.32)	1.20 (1.24)	0.80 (1.07)	0.90 (1.09)	1.30 (1.28)	1.20 (1.26)	2.50 (1.68)	1.10 (1.23)	0.60 (0.99)	1.00 (1.18)	0.30 (0.85)	
	T3	1.00 (1.21)	1.10 (1.23)	1.50 (1.36)	1.20 (1.26)	1.00 (1.19)	0.50 (0.97)	1.00 (1.18)	1.10 (1.20)	1.00 (1.18)	1.50 (1.37)	1.00 (1.19)	1.00 (1.15)	1.00 (1.19)	0.40 (0.90)	
	T4	1.10 (1.23)	0.70 (1.02)	1.10 (1.23)	1.00 (1.15)	0.60 (0.99)	0.50 (0.94)	0.70 (1.04)	0.40 (0.90)	0.60 (1.00)	1.50 (1.36)	0.70 (1.05)	0.90 (1.14)	0.50 (0.95)	0.20 (0.81)	
D2	T1	0.90 (1.14)	0.40 (0.90)	0.90 (1.10)	0.90 (1.12)	0.30 (0.86)	0.30 (0.86)	0.40 (0.90)	0.60 (1.00)	0.40 (0.91)	1.40 (1.32)	0.60 (1.02)	0.30 (0.85)	0.60 (0.99)	0.00 (0.71)	0.69 (1.03)b
	T2	1.20 (1.25)	1.10 (1.20)	1.20 (1.25)	1.30 (1.28)	0.50 (0.94)	0.30 (0.85)	0.90 (1.12)	0.70 (1.02)	0.80 (1.09)	2.20 (1.61)	0.80 (1.07)	1.30 (1.29)	1.00 (1.18)	0.30 (0.86)	
	T3	1.10 (1.18)	0.60 (0.99)	1.00 (1.15)	0.30 (0.85)	0.90 (1.14)	0.30 (0.86)	0.90 (1.12)	1.00 (1.15)	0.70 (1.02)	1.50 (1.35)	0.50 (0.95)	0.90 (1.14)	0.80 (1.07)	0.30 (0.85)	
	T4	1.00 (1.19)	0.50 (0.95)	0.60 (0.99)	0.50 (0.95)	0.50 (0.95)	0.20 (0.81)	0.60 (1.00)	0.40 (0.91)	0.50 (0.95)	0.80 (1.09)	0.20 (0.81)	0.20 (0.81)	0.40 (0.91)	0.00 (0.71)	
D3	T1	1.00 (1.19)	0.60 (1.00)	1.10 (1.23)	0.50 (0.94)	0.30 (0.85)	0.40 (0.91)	0.60 (1.00)	0.70 (1.04)	0.50 (0.97)	1.20 (1.26)	0.40 (0.90)	0.30 (0.86)	0.70 (1.05)	0.20 (0.81)	0.77 (1.07)b
	T2	1.30 (1.27)	1.20 (1.26)	1.20 (1.25)	1.00 (1.18)	1.00 (1.18)	0.70 (1.04)	1.00 (1.18)	1.10 (1.24)	0.50 (0.91)	2.20 (1.57)	0.90 (1.12)	1.00 (1.16)	1.10 (1.21)	0.70 (1.05)	
	T3	1.10 (1.24)	1.10 (1.21)	1.20 (1.23)	1.10 (1.20)	0.50 (0.94)	0.80 (1.07)	0.90 (1.12)	1.00 (1.18)	1.20 (1.26)	1.40 (1.30)	0.70 (1.05)	1.00 (1.15)	0.50 (0.93)	0.60 (1.00)	
	T4	0.40 (0.90)	0.30 (0.86)	0.80 (1.07)	0.30 (0.85)	0.70 (1.05)	0.50 (0.97)	0.40 (0.91)	0.50 (0.95)	0.70 (1.07)	0.80 (1.09)	0.30 (0.86)	0.40 (0.90)	0.60 (1.02)	0.00 (0.71)	
D4	T1	0.60 (1.00)	0.40 (0.90)	1.00 (1.18)	0.50 (0.95)	0.60 (1.00)	0.30 (0.85)	0.70 (1.07)	0.50 (0.97)	0.30 (0.86)	1.30 (1.28)	0.60 (1.00)	0.60 (1.02)	0.60 (1.00)	0.10 (0.76)	0.76 (1.06)b
	T2	1.20 (1.26)	1.20 (1.24)	1.20 (1.22)	1.20 (1.25)	1.20 (1.24)	0.60 (0.98)	1.00 (1.18)	1.20 (1.26)	1.00 (1.15)	2.00 (1.53)	1.10 (1.21)	1.10 (1.23)	0.90 (1.11)	0.70 (1.05)	
	T3	0.90 (1.12)	1.00 (1.18)	1.00 (1.18)	1.10 (1.21)	0.90 (1.14)	0.40 (0.91)	0.70 (1.05)	0.50 (0.94)	1.10 (1.21)	1.00 (1.19)	0.90 (1.15)	0.80 (1.10)	0.90 (1.14)	0.30 (0.85)	
	T4	1.00 (1.19)	0.40 (0.90)	0.80 (1.09)	0.70 (1.05)	0.50 (0.94)	0.40 (0.90)	0.70 (1.05)	0.50 (0.95)	0.70 (1.04)	0.30 (0.85)	0.30 (0.85)	0.50 (0.95)	0.40 (0.90)	0.10 (0.76)	
Species mean		1.02 (1.18) bc	0.79 (1.07)d	1.09 (1.20)b	0.88 (1.11)cd	0.72 (1.04)d	0.47 (0.93)e	0.77 (1.07)d	0.76 (1.06)d	0.74 (1.06)d	1.44 (1.32)a	0.68 (1.03)d	0.71 (1.04)d	0.74 (1.06)d	0.28 (0.84)f	Overall CV= 32.26
Time mean		T1			T2			T3				T4				
		0.64 (1.01)c			1.08 (1.19)a			0.89 (1.12)b				0.55 (0.97)d				

ANOVA

Source	Df	Sum of square	Mean sum of square	F value	Pr (>F)
Species	13	26.870	2.067	17.247	<0.001
Time	3	16.440	5.481	45.746	<0.001
Week	3	3.640	1.213	10.125	<0.001
Species × Time	39	4.540	0.116	0.971	0.522
Species × Week	39	2.800	0.072	0.600	0.977
Time × Week	9	0.580	0.064	0.535	0.850
Species × Time × Week	117	8.060	0.069	0.575	1.000
Error	2016	241.56	0.120		

Note: Means suffixed with different letters are significantly different. Figures in the parenthesis are square root (\sqrt{x+0.5}) transformed values. D1-D4 indicate respective observational weeks. T1-T4 indicate respective observational times. Sp1-Sp14 indicate different bee pollinators as mentioned in Table 2, where Sp10* represents the data of two species which were difficult to distinguish in field condition.

Estimation of different ecological indices

The ecological indices for species diversity, richness, evenness, and dominance have been presented in Table 4. Here we have noted quite higher values for Shannon diversity and Margalef richness indices for all the observational units. Sheldon evenness index of all the observational units showed higher values tending to 1, and Simpson dominance index showed lower values tending to 0. Meanwhile, Shannon diversity and Margalef richness indices were recorded higher in 2023 than in 2022. The time period of 10:00–12:30 hours was characterized by a higher Shannon diversity index than the remaining time intervals. Furthermore, the diversity index was highest during the 3rd week of observation or flowering (D3) than the remaining weeks in both years.

Table 4. Ecological indices for different bee pollinators observed in litchi bloom (S=15).

Year	Parameter		Ecological indices			
			H'	Da	E	D
2022	Time	07:00–10:00	2.582	3.907	0.881	0.082
		10:00–12:30	2.663	3.366	0.956	0.072
		12:30–15:00	2.661	3.547	0.954	0.072
		15:00–17:30	2.565	4.166	0.867	0.083
	Date	D1	2.576	3.496	0.939	0.080
		D2	2.663	3.425	0.956	0.072
		D3	2.673	3.605	0.965	0.071
		D4	2.408	4.069	0.741	0.078
	Cumulative		2.650	2.694	0.944	0.073
2023	Time	07:00–10:00	2.665	3.901	0.958	0.072
		10:00–12:30	2.690	3.460	0.982	0.069
		12:30–15:00	2.669	3.624	0.961	0.072
		15:00–17:30	2.565	4.004	0.867	0.075
	Date	D1	2.688	3.361	0.980	0.069
		D2	2.433	4.152	0.877	0.096
		D3	2.689	3.854	0.974	0.070
		D4	2.501	3.513	0.813	0.069
	Cumulative		2.686	2.714	0.978	0.069
Pooled data of two year			2.672	2.385	0.965	0.071

Note: S = numbers of species; H′ = Shannon diversity index; Da = Margalef richness index; E = Sheldon evenness index; and D=Simpson dominance index.

Assessment of foraging rate

As presented in Table 5, the ANOVA table suggested the significant impact ($p<0.001$) of all the main effects on the foraging rate. Both the bees from the Megachilidae family, i.e., *M. laticeps* (Sp14) and *Heriades* sp. (Sp13), were found to visit a significantly greater number of flowers than other bees, with a foraging rate of 13.96 and 13.87 flowers visited/minute/forager, respectively. Conversely, *H. floralis* (Sp9) was recorded with the least foraging rate, visiting only 8.73 flowers/minute/forager. Bees were noted to visit more flowers at 10:00–12:30 hours (T2). Foraging rate was also highest during the first week of observation (D1) and then decreased steadily, a trend similar to the weekly and time-wise variation in forager abundance. Furthermore, the significant species-time and species-week interactions tell us that the foraging rate of a particular bee species depended on the time of the day and observational week and was significantly higher (3.89 flowers visited/minute/forager) for *Heriades* sp. (Sp13) at 10:00–12:30 hours (T2) and for *M. laticeps* (Sp14) during the first week of observation (D1) than the other species-time and species-week interactions, respectively.

Table 5. Assessment of foraging rate (as number of flowers visited/minute/forager) of different bee pollinators in litchi bloom at different weeks and times from pooled data of two years using missing plot three-factor factorial ANOVA and DNMRT post-hoc test (α=0.05) with n=1895 no. of observations.

Week	Time	Species														Weekly mean
		Sp1	Sp2	Sp3	Sp4	Sp5	Sp6	Sp7	Sp8	Sp9	Sp10*	Sp11	Sp12	Sp13	Sp14	
D1	T1	10.70 (3.34)	12.40 (3.59)	11.90 (3.52)	11.50 (3.45)	12.30 (3.57)	10.90 (3.37)	10.60 (3.33)	11.30 (3.43)	8.70 (3.03)	11.90 (3.52)	11.90 (3.52)	11.70 (3.49)	13.50 (3.74)	14.80 (3.91)	12.12 (3.54)a
	T2	12.80 (3.65)	14.00 (3.81)	13.50 (3.74)	13.20 (3.70)	12.60 (3.62)	12.60 (3.62)	12.70 (3.63)	12.80 (3.64)	9.50 (3.16)	12.60 (3.62)	12.90 (3.66)	13.60 (3.75)	14.80 (3.91)	15.40 (3.99)	
	T3	12.50 (3.61)	13.20 (3.70)	13.20 (3.70)	12.80 (3.64)	12.40 (3.59)	12.50 (3.60)	12.30 (3.57)	12.60 (3.62)	8.80 (3.05)	9.70 (3.15)	12.40 (3.58)	12.80 (3.65)	14.40 (3.86)	14.60 (3.88)	
	T4	10.50 (3.31)	11.90 (3.52)	11.50 (3.46)	11.20 (3.41)	12.00 (3.53)	11.60 (3.48)	10.40 (3.30)	10.60 (3.32)	8.60 (3.02)	11.30 (3.43)	11.50 (3.46)	11.50 (3.46)	12.90 (3.66)	13.60 (3.75)	
D2	T1	11.30 (3.43)	12.40 (3.59)	11.70 (3.49)	11.00 (3.39)	12.40 (3.59)	11.00 (3.38)	11.00 (3.39)	11.20 (3.42)	8.60 (3.00)	12.10 (3.55)	12.40 (3.59)	11.60 (3.48)	13.10 (3.69)	-	11.97 (3.52) ab
	T2	12.40 (3.59)	13.1 (3.68)	12.90 (3.66)	12.60 (3.62)	12.80 (3.64)	13.00 (3.66)	12.80 (3.64)	13.20 (3.70)	9.10 (3.09)	12.40 (3.59)	13.00 (3.67)	13.10 (3.69)	14.80 (3.91)	13.80 (3.78)	
	T3	11.90 (3.52)	13.20 (3.70)	12.50 (3.60)	11.40 (3.45)	12.10 (3.55)	12.80 (3.65)	12.50 (3.60)	12.40 (3.59)	9.40 (3.14)	9.20 (3.07)	12.80 (3.65)	12.70 (3.63)	14.40 (3.86)	13.60 (3.75)	
	T4	10.90 (3.37)	12.00 (3.53)	11.80 (3.51)	11.00 (3.39)	11.50 (3.46)	10.80 (3.35)	10.50 (3.31)	11.40 (3.44)	8.40 (2.98)	8.80 (3.00)	12.00 (3.54)	11.40 (3.45)	14.00 (3.80)	-	
D3	T1	11.40 (3.44)	11.90 (3.52)	11.80 (3.50)	11.40 (3.45)	12.00 (3.53)	11.20 (3.41)	11.20 (3.42)	11.10 (3.40)	8.20 (2.95)	9.20 (3.07)	11.80 (3.50)	11.20 (3.42)	13.60 (3.75)	13.60 (3.75)	11.84 (3.50)b
	T2	12.20 (3.56)	13.30 (3.71)	13.00 (3.67)	12.70 (3.63)	12.50 (3.60)	12.40 (3.59)	12.60 (3.62)	12.70 (3.63)	9.00 (3.08)	12.30 (3.58)	12.90 (3.66)	12.80 (3.64)	14.60 (3.88)	14.20 (3.83)	
	T3	12.40 (3.59)	12.90 (3.66)	12.20 (3.56)	12.50 (3.60)	12.60 (3.62)	12.10 (3.55)	12.20 (3.56)	12.50 (3.60)	8.70 (3.03)	9.10 (3.06)	12.60 (3.62)	12.50 (3.60)	14.40 (3.85)	13.70 (3.77)	
	T4	11.20 (3.42)	12.00 (3.53)	11.50 (3.46)	11.20 (3.42)	11.80 (3.50)	10.90 (3.37)	10.80 (3.36)	11.10 (3.41)	8.40 (2.98)	8.50 (2.96)	11.20 (3.42)	11.20 (3.42)	12.90 (3.66)	-	
D4	T1	10.40 (3.29)	12.60 (3.62)	11.80 (3.51)	11.60 (3.48)	12.00 (3.53)	11.60 (3.48)	11.20 (3.42)	11.10 (3.40)	8.40 (2.98)	11.60 (3.47)	11.70 (3.49)	11.60 (3.48)	13.00 (3.67)	14.40 (3.86)	11.74 (3.49)b
	T2	12.20 (3.56)	13.20 (3.70)	13.10 (3.69)	12.50 (3.59)	12.50 (3.60)	12.20 (3.56)	12.20 (3.55)	12.50 (3.60)	9.20 (3.11)	12.40 (3.59)	12.60 (3.61)	12.90 (3.66)	14.30 (3.85)	13.20 (3.69)	
	T3	12.50 (3.60)	12.80 (3.65)	12.20 (3.56)	12.40 (3.59)	12.20 (3.56)	11.90 (3.52)	12.10 (3.55)	12.80 (3.64)	8.50 (2.99)	6.20 (2.59)	12.20 (3.56)	12.50 (3.60)	14.10 (3.82)	14.40 (3.86)	
	T4	10.20 (3.26)	12.20 (3.56)	11.30 (3.43)	11.20 (3.42)	12.00 (3.53)	11.40 (3.45)	11.10 (3.40)	10.90 (3.37)	8.20 (2.95)	6.00 (2.55)	11.80 (3.50)	11.60 (3.47)	13.00 (3.67)	13.40 (3.73)	
Species mean		11.61 (3.47)d	12.76 (3.64)b	12.26 (3.57)c	11.99 (3.53) cd	12.22 (3.56)c	11.82 (3.50)d	11.69 (3.48)d	11.87 (3.51) cd	8.73 (3.03)f	10.34 (3.26)e	12.26 (3.57)c	12.26 (3.57)c	13.87 (3.79)a	13.96 (3.80)a	Overall CV= 6.11
Time mean		T1			T2			T3				T4				
		11.54 (3.46)c			12.69 (3.63)a			12.10 (3.54)b				11.12 (3.39)d				

ANOVA

Source	Df	Sum of square	Mean sum of square	F value	Pr (>F)
Species	13	61.64	4.74	102.23	<0.001
Time	3	13.58	4.53	97.58	<0.001
Week	3	0.92	0.31	6.63	<0.001
Species × Time	39	10.18	0.26	5.63	<0.001
Species × Week	39	2.59	0.07	1.43	0.04
Time × Week	9	0.31	0.03	0.74	0.67
Species × Time × Week	114	5.05	0.04	0.96	0.61
Error	1674	77.65	0.05		

Note: Means suffixed with different letters are significantly different. Figures in the parenthesis are square root (sqrt{x+0.5}) transformed values. D1-D4 indicate respective observational weeks. T1-T4 indicate respective observational times. Sp1-Sp14 indicate different bee pollinators as mentioned in Table 2, where Sp10* represents the data of two species which were difficult to distinguish in field condition. The blank cells indicate the absence of that particular bee species during that week at that time.

Assessment of foraging speed

Our data revealed that the foraging speed also significantly differed ($p<0.001$) with observational weeks, times, and bee species (Table 6). As mentioned in the previous section, *H. floralis* (Sp9), which used to visit a significantly lesser number of flowers per minute, was found to spend a significantly greater time on each flower (i.e., 4.48 seconds). In contrast, both the bees from the Megachilidae family that showed the highest foraging rate were recorded with the significantly least foraging speed. Foraging speed also peaked at 10:00–12:30 hours (T2) during the first week of observation (D1) and then gradually decreased with passing time and week.

Table 6. Assessment of foraging speed (in seconds) of different bee pollinators in litchi bloom at different weeks and times from pooled data of two years using missing plot three-factor factorial ANOVA and DNMRT post-hoc test (α=0.05) with n=1895 no. of observations.

Week	Time	Species														Weekly mean
		Sp1	Sp2	Sp3	Sp4	Sp5	Sp6	Sp7	Sp8	Sp9	Sp10*	Sp11	Sp12	Sp13	Sp14	
D1	T1	3.40	3.11	3.26	3.17	2.60	2.81	2.56	2.74	3.83	3.22	3.14	3.05	2.26	2.05	3.38a
	T2	4.29	3.94	4.14	4.00	3.57	3.58	3.80	3.93	5.51	4.13	4.24	4.37	2.39	2.44	
	T3	4.17	3.89	4.05	3.93	3.55	3.57	3.73	3.58	4.90	2.88	4.22	3.91	2.19	2.15	
	T4	3.27	3.09	3.13	3.12	2.67	2.47	2.52	2.71	4.04	3.03	3.08	3.12	2.16	2.02	
D2	T1	3.62	3.17	3.07	3.05	2.85	3.21	2.89	2.70	4.02	3.16	2.93	3.03	2.33	-	3.36a
	T2	4.20	3.83	4.01	3.95	3.85	3.70	3.79	4.00	5.48	3.73	4.46	4.30	2.28	2.31	
	T3	3.41	4.03	3.78	3.41	3.54	3.62	3.66	3.29	5.48	2.63	4.36	3.50	2.11	2.24	
	T4	3.17	3.13	3.31	3.21	2.57	3.26	2.50	2.87	4.31	2.23	3.29	3.01	2.58	-	
D3	T1	3.55	3.07	3.21	3.19	2.62	2.80	2.60	2.71	4.01	2.22	3.07	3.11	2.26	2.181	3.33a
	T2	4.19	4.04	4.15	4.11	3.58	3.58	3.80	3.99	5.06	3.88	4.20	4.27	2.20	2.343	
	T3	4.12	3.93	4.05	4.01	3.71	3.49	3.65	3.65	4.81	2.87	3.81	3.92	2.36	2.198	
	T4	3.05	3.06	3.17	3.08	2.65	2.71	2.22	2.58	3.97	2.29	2.94	2.74	2.44	-	
D4	T1	3.49	3.13	3.12	3.17	2.72	2.50	2.57	2.67	4.03	2.86	2.98	3.02	2.28	2.02	3.23b
	T2	4.24	3.75	4.10	3.98	3.57	3.00	3.58	3.91	4.39	3.70	4.20	4.27	2.25	2.35	
	T3	4.05	3.70	3.82	3.91	3.29	3.49	3.58	3.53	4.11	1.78	3.91	4.01	2.07	2.13	
	T4	3.16	3.08	3.19	3.22	2.68	2.42	2.55	2.37	3.79	1.32	2.66	3.04	2.09	1.97	
Species mean		3.73b	3.55b	3.61b	3.59b	3.14c	3.17c	3.16c	3.19c	4.48a	2.92d	3.62b	3.62b	2.26e	2.20e	Over-all CV= 21.27
Time mean		T1		T2			T3				T4					
		2.94c		3.80a			3.55b				2.87c					

ANOVA					
Source	Df	Sum of square	Mean sum of square	F value	Pr (>F)
Species	13	562.10	43.24	87.28	<0.001
Time	3	309.50	103.17	208.24	<0.001
Week	3	8.60	2.87	5.80	<0.001
Species × Time	39	84.70	2.17	4.38	<0.001
Species × Week	39	25.00	0.64	1.30	0.11
Time × Week	9	4.00	0.45	0.90	0.52
Species × Time × Week	114	30.20	0.26	0.53	0.10
Error	1674	829.30	0.50		

Note: Means suffixed with different letters are significantly different. D1-D4 indicate respective observational weeks. T1-T4 indicate respective observational times. Sp1-Sp14 indicate different bee pollinators as mentioned in Table 2, where Sp10* represents the data of two species which were difficult to distinguish in field condition. The blank cells indicate the absence of that particular bee species during that week at that time.

Impact of weather factors on foraging parameters

Our study showed a significant impact of various weather factors on different foraging attributes of bees. For instance, T_{max} and BSH showed significantly positive correlations with forager abundance. Similarly, foraging rate and speed were also found to be positively and significantly influenced by BSH and T_{max}, respectively. On the other hand, RH_{min} and wind speed showed a significantly negative correlation with the foraging speed and forager abundance. Despite the occurrence of low rainfall during the study period, this factor also had a noticeable negative impact on different foraging parameters. As presented in Fig. 3, only a small amount of rainfall took place at the 4th week of flowering (D4) in 2022. Meanwhile, abundance was found to have significantly positive correlations with foraging rate (r = 0.92, p<0.01) and speed (r = 0.80, p<0.05) (Fig. 4), indicating the bees visiting more flowers and spending more time on each flower with increasing pollinator abundance.

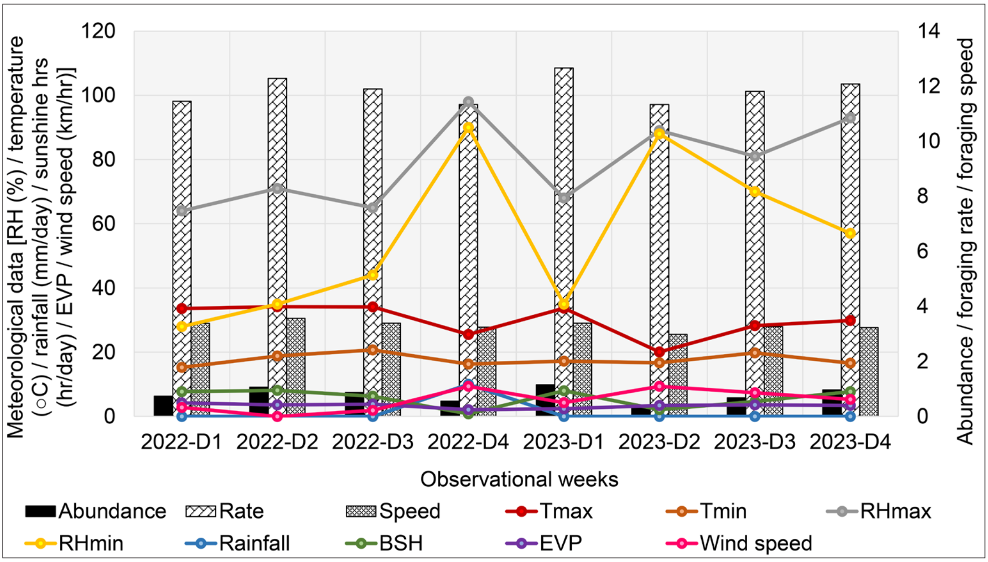

Figure 3. Changes in the foraging parameters in relation to weather factors.

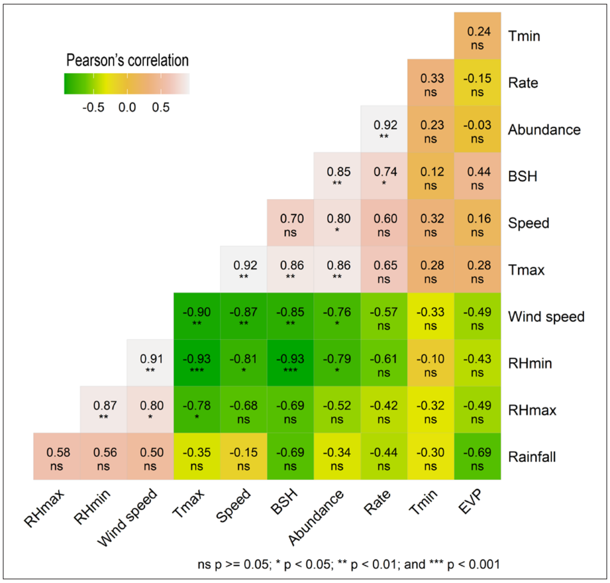

Figure 4. Pearson's correlation of different weather factors on forager abundance foraging rate, and foraging speed.

CONCLUSIONS AND DISCUSSION

Litchi is one of those crops for which cross-pollination is the best way to reproduce (Trueman & Nichols, 2025) due to its typical flowering pattern (Stern & Gazit, 1996; Lal et al., 2021a). In this context, the importance of different insect pollinators, specifically bees, is enormous (Pandey & Yadava, 1970; Kumari et al., 2023), as the pollen of litchi remains viable for several days on the pollinator bodies until the receptive stigmas become available (Liu, 1954). In our present study, we have documented a good bee diversity, comprising 15 species of bee visitors, associated with litchi bloom from the sub-Himalayan Terai region of West Bengal. This number is notably larger than the bee assemblage associated with litchi recorded from other parts of India (Abrol, 2006; Srivastava et al., 2017; Das et al., 2019; Kumari et al., 2023, 2024; Wahid & Singh, 2024). The presence of such greater diversity has also been reflected in the higher values of Shannon diversity and Margalef richness indices (Table 4) during both study years. Actually, this region is characterized by a good diversity of bee forages (Saha, Nath, Dey, Laskar, & Kundu, 2023), creating a suitable habitat for the availability of different bee species. Furthermore, the study was conducted in the spring months (March-April), a period when the environmental conditions transit from harsh winter to more favorable situations for bee activity (Villagomez, Nürnberger, Requier, Schiele, & Steffan-Dewenter, 2021; Nath et al., 2024), coinciding with the blooming of various flora, which can explain the reason for getting a higher species diversity during this timeframe.

Honey bees contribute a good fraction of the total bee assemblage. The role of different honey bee species, specifically *A. mellifera*, in pollination and fruit setting of litchi is well known (Rai & Srivastav, 2012; Kumar & Kumar, 2014; Kumari et al., 2023) and has been a subject of global consensus. Although our study has documented Sp10 as the most abundant bee species with a mean abundance of 1.44 individuals/m^2/minute. However, Sp10 demonstrated two morphologically quite similar bee species, i.e., *L. albescens* and *L. cavernifrons*, which were difficult to distinguish while taking the field observations. That's why we can also consider the second most abundant bee species, i.e., *A. mellifera*, with a mean abundance of 1.09 individuals/m^2/minute, as the most abundant one. From our study region, we have recorded three species of honey bees, except *A. florea*, indicating this honey bee species may not be available in this region.

Besides honey bees, we have also recorded a great proportion of solitary bees pollinating litchi blooms, showcasing their importance in litchi pollination, which many times remains unnoticed. Among them, species of *Andrena*, *Braunsapis*, *Ceratina*, *Hylaeus*, *Lasioglossum*, *Seladonia*, and *Heriades* have a good abundance, except for *M. laticeps*, which constituted only 2.48% of the total bee abundance. However, in our study, the diversity measures indicated high evenness and low dominance in the sampled bee assemblage during both years. Here, the recorded values for the Sheldon evenness index were close to 1, indicating a nearly perfect distribution of abundances. This was also justified by the lower values of the Simpson dominance index (tended towards 0) in both years, indicating no dominance by a single or few species in the assemblage (Heip, 1974; Kanieski, Longhi, & Soares, 2018). This situation clarifies that, even after the lower abundance of *M. laticeps*, this species was also relatively important as the other abundant bee species. In addition, the bee assemblage in 2023 was characterized by higher diversity and species richness coupled with low dominance and high evenness as compared to the bee assemblage in 2022.

Our study revealed that the time interval 10:00-12:30 hours is that particular period when the bees are more abundant and active in litchi bloom. During this timeframe, bees visit a greater number of flowers and allocate more time to each flower, consistent with the timeframe documented by other workers as the peak period for bee foraging in litchi bloom (Singh, Kumar, & Chand, 2002; Kumar, Sharma, & Khan, 2013; Kumari et al., 2024). Furthermore, this time interval was also characterized by a higher Shannon diversity index. There might be different reasons responsible for this phenomenon, of which the environmental temperature might be the one that significantly impacts the local abundance and distribution of pollinators (Li et al., 2025). Usually, different groups of pollinators show differences in their temperature preference, where the bees used to prefer and become more abundant in the hotter climates (McCall & Primack, 1992; Hegland, Nielsen, Lázaro, Bjerknes, & Totland, 2009). Weather factors always have a significant influence on the bees' foraging behavior, despite the capacity of some bees to adapt to temperature changes via thermoregulation (Barreiro, Ratoni, Baena-Díaz, González-Tokman, & Dáttilo, 2024). Our study also showed a significantly positive correlation between temperature and abundance of bee pollinators. As the study was conducted during the spring months, the atmospheric temperature was low at early morning hours (i.e., 07:30-10:00 hours), causing lesser bee activity at that time interval. Thereafter, during 10:00-12:30 hours, the atmospheric temperature got high enough, providing an ample climate for bees to forage, and then again declined with time. In addition to the environmental temperature, the occurrence of anthesis and availability of nectar can also influence the bee foraging activity (Kamaraj & Rasappan, 2024). Usually, in litchi, maximum anthesis and nectar secretion take place in early morning, up to 10:00 hours (Stern & Gazit, 1996; Pathak, Ray, & Mitra, 2013), enabling a profuse amount of floral rewards available for the bees coupled with ample environmental temperature during 10:00-12:30 hours. These are certain possible justifications for getting a higher bee abundance and activity at that specific time interval.

Abundance was highest during the first week of flowering (D1), i.e., during mid-March, which is in line with the results of Rai, Srivastava, Bisht, & Mishra (2017) from a quite similar agro-climatic region. Thereafter, there was a decline in the bee abundance in the later weeks of observation, which might be attributed to the lack of available floral resources due to the initiation of fruiting. Moreover, the occurrence of flower drop due to various environmental and anthropogenic factors can also lead to a reduction in floral availability at those later observational weeks, diverting the bees to look for other foraging sources thereby. This may explain the occurrence of low bee abundance at later weeks of observation.

Another weather factor that has a significantly positive impact on bee abundance is bright sunny hours. From Fig. 3, it is clear that the days with more bright sunny hours have a greater bee abundance. In general, temperature and solar effects always have positive correlations with the foraging activity of bees (Corbet et al., 1993; Abrol, 2006; Clarke & Robert, 2018; Nath et al., 2024). Unlike temperature and bright sunny hours, rainfall, relative humidity, and wind speed were the factors having negative impacts on the bee activity. Usually, the presence of wind makes the flight of bees a challenging task. A greater wind speed initiates hesitation in bees during take-off and makes it difficult for the bees to achieve proper flight orientation, movement, and landing dynamics, hence reducing their foraging efficiency (Hennessy et al., 2020, 2021). Although, during the study, we haven't encountered rain that much, except for a short spell of rainfall that took place on D4 of 2022, coupled with high relative humidity, greater wind speed, and low temperature (Fig. 3), can justify the occurrence of low abundance and less foraging activity on that particular week. Such negative effects of rainfall, wind speed, and relative humidity on bee pollinator activity have also been recorded by other researchers (Abrol, 2006; Lawson & Rands, 2019; Karbassioon et al., 2023; Kumari et al., 2023; Nath et al., 2024; Nath, Saha, & Laskar, 2024).

In addition to the weather factors, forager abundance also had significant positive correlations with foraging rate and speed, indicating the bees becoming more active with increasing abundance. In a flowering ecosystem with diverse pollinator species, an increase in pollinator abundance compels individuals within the community to confront heightened levels of interspecific and intraspecific competition for floral resources (Inouye, 1978). For that, the bees need to visit more flowers and harvest more floral resources in order to sustain themselves in that competition. That's why time-wise and weekly variation in the foraging rate and speed follow the trend similar to forager abundance. At 10:00–12:30 hours (T2) during the first week of flowering (D1), when the forager abundance was maximum, the bees used to visit a greater number of flowers and spend more time in each flower in order to harvest a greater amount of floral resources and might spend less time on aerial flight at that point. Our data on foraging parameters of different bee pollinators in litchi is almost following and sometimes slightly varying from other published literatures (Singh et al., 2002; Kumar et al., 2013; Srivastava et al., 2017; Dubey, Thapa, Tiwari, Gautam, & Sapkota, 2020; Kumari et al., 2024). This variation might be attributed by the difference in the region, prevailing environmental conditions, foraging sources, pollinator species composition, etc.

Our study provides crucial insights about the diversity and foraging behaviour of bee pollinators in litchi bloom. This information may help the litchi growers of the sub-Himalayan Terai region of West Bengal to enhance the litchi production. Furthermore, there are proven evidences that bee pollination could improve the critical quality attributes of the crop produce (Aristizábal et al., 2025). Therefore, in order to achieve a greater litchi yield with quality produce, the search for its potential pollinators and conserving their diversity is a prerequisite. Our data reveals that different solitary bees might play a crucial role in litchi pollination, which is also supported by other researchers (Jamwal & Thakur, 2019). So, employing the honey bee pollination service coupled with the conservation of these solitary bees can provide an extraordinary fruit setting in litchi. Substantial enhancement in solitary bee diversity in litchi can be achieved by providing resource-rich crops or flowering weeds in the surroundings of litchi orchards. In addition, cautious application of insecticides in the litchi orchard needs to be done during the active foraging period of the bees to avoid bee mortality. Although it is a region-specific study, we still believe that the information obtained in our study, specifically regarding the pollination attributes of these bee pollinators, can be effectively employed in other regions in order to enhance the pollination of litchi crops.

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