Diversity and Foraging Behavior of Bees (Hymenoptera: Apoidea) on *Hyptis Suaveolens* in Abu Road, Rajasthan, India

Mahendra Devanda[1], Dr. Santosh Kumar Charan[2]

[1]Seth R. L. Saharia Government PG College, Kaladera, Jaipur, Rajasthan, India

[2]Department of Zoology, University of Rajasthan, Jaipur, India
Corresponding Author Email: skumarcharan[at]gmail.com

Abstract: ***The present study investigates the diversity and foraging behaviour of bees associated with Hyptis suaveolens (Lamiaceae) in Abu Road tehsil of Sirohi district, Rajasthan, India. Field observations were conducted from April 2022 to June 2024 across different habitats including scrublands, agricultural fields, forest margins, and riverine areas. Standard visual observation techniques and sweep net sampling were employed to document bee diversity and visitation frequency. Microclimatic parameters such as temperature, relative humidity, and wind velocity were also recorded to analyze their influence on bee foraging activity. A total of 13 bee species belonging to eight genera and three families (Apidae, Megachilidae, and Halictidae) were recorded visiting the flowers of H. suaveolens. The family Apidae was dominant, contributing 53.85% of the total recorded species, followed by Megachilidae (30.77%) and Halictidae (15.38%). The most frequent floral visitors were Apis dorsata, Apis florea, and Amegilla zonata. Peak foraging activity was observed during morning hours (08:00-11:00 h). Seasonal variation showed the highest visitation rate in April (17 bees min^{-1}) under moderate temperature (30°C), low humidity (26%), and moderate wind velocity (3.06 m s^{-1}). Correlation analysis indicated a positive relationship between temperature and foraging activity, whereas humidity and wind velocity showed negative correlations. The results highlight the ecological importance of H. suaveolens as a significant nectar source for sustaining bee diversity in semi-arid ecosystems of the Aravalli region.***

Keywords: Bee diversity, Foraging behavior, *Hyptis suaveolens*, Pollination ecology, Abu Road, Semi-arid ecosystem

1. Introduction

Pollination is a fundamental ecological process that ensures the reproduction of flowering plants and the maintenance of biodiversity in terrestrial ecosystems. A large proportion of angiosperms rely on animal-mediated pollination, with approximately 87% of flowering plant species depending on animal pollinators for successful reproduction (Ollerton et al., 2011). Among these pollinators, bees are recognized as one of the most efficient and diverse groups due to their specialized morphology and behavior that facilitate effective pollen transfer (Michener, 2007). Pollination services are also critical for global food production, as nearly 75% of the world's leading food crops benefit from animal pollination, thereby contributing significantly to food security and agricultural sustainability (Klein et al., 2007). The global economic value of pollination services has been estimated to reach hundreds of billions of US dollars annually, highlighting their substantial contribution to the world economy (Gallai et al., 2009).

Despite their immense ecological and economic importance, pollinators are experiencing widespread declines across many regions of the world. Multiple interacting drivers have been identified as major causes of these declines, including habitat loss, agricultural intensification, pesticide exposure, pathogens, invasive species, and climate change (Potts et al., 2010; Goulson et al., 2015). Climate change, in particular, is emerging as a significant factor influencing the distribution and diversity of pollinators. Rising temperatures and changing climatic patterns are predicted to alter the global distribution of bee species, leading to shifts in climatic suitability across different regions (Rahimi & Jung, 2024). Additionally, climate-induced changes in flowering phenology may result in spatial and temporal mismatches between flowering plants and their pollinators, potentially disrupting plant–pollinator interactions (Parmesan, 2006; Rahimi & Jung, 2025).

The importance of pollinators in maintaining ecosystem stability has been emphasized in global assessments such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services report, which highlights the crucial role of wild pollinators in supporting ecosystem resilience, particularly in semi-natural and agro-ecological landscapes (IPBES, 2016). A decline in pollinator diversity may therefore negatively affect plant reproductive success, alter plant community composition, and reduce overall ecosystem stability. Bees belonging to the superfamily Apoidea (Order Hymenoptera) exhibit diverse ecological strategies and functional traits that enhance pollination efficiency. Social bee species such as *Apis dorsata* and *Apis florea* play a dominant role in pollination within tropical and subtropical regions of Asia (Abrol, 2012). In addition, solitary and semi-social bee taxa, including Amegilla zonata, Megachile species, Ceratina species, and Xylocopa species, often demonstrate high pollination efficiency due to floral specialization, rapid foraging behavior, and strong floral constancy (Roubik, 1989). The presence of multiple bee species within a community can lead to functional complementarity, where different species contribute uniquely to pollination processes, thereby enhancing the stability and resilience of plant–pollinator networks (Memmott et al., 2004; Bascompte & Jordano, 2007).

Semi-arid ecosystems, such as those of western India, are characterized by erratic rainfall, high evapotranspiration, and pronounced seasonal variability (Whitford, 2002). Floral resource availability in these landscapes is temporally patchy, creating seasonal bottlenecks for pollinator populations (Minckley & Roulston, 2006). Wild flowering shrubs and herbaceous plants therefore act as essential nectar and pollen reservoirs during periods when cultivated crops are absent (Winfree et al., 2009; Garibaldi et al., 2013). Recent research further indicates that landscape heterogeneity significantly correlates with bee richness and pollen diversity, emphasizing the importance of structurally complex habitats for sustaining pollinator assemblages (Landscape heterogeneity study, 2024).

The Aravalli hill range, one of the oldest geological formations in the world, supports heterogeneous vegetation mosaics ranging from dry deciduous forests to scrublands (Rodgers & Panwar, 1988). The southern Aravalli region, including Abu Road tehsil in Sirohi district, Rajasthan, comprises rocky hill slopes, riverine tracts, and fragmented forest patches. These habitats provide diverse nesting substrates such as exposed soil banks, woody debris, and rock crevices essential for solitary and social bees (Cane, 2001). However, systematic pollinator documentation in this semi-arid transitional landscape remains limited (Saini & Kundu, 2011). Region-specific ecological assessments are therefore critical for understanding pollinator assemblage structure and climatic sensitivity.

Wild flowering plants form the structural backbone of pollinator-supporting habitats. Greater floral diversity enhances pollinator richness and strengthens interaction networks, thereby increasing ecological stability (Bascompte & Jordano, 2007). Members of the family Lamiaceae are particularly attractive to bees due to their bilabiate corollas, nectar guides, and glandular trichomes (Harley et al., 2004; Willmer, 2011). Floral traits such as corolla morphology, nectar volume, and sugar concentration significantly influence pollinator visitation frequency and network configuration (Nicolson & Thornburg, 2007; Akka et al., 2025). Studies from semi-arid and Mediterranean ecosystems demonstrate that habitat structure and floral trait diversity jointly shape plant-pollinator interactions and network resilience (Michael et al., 2025).

H. suaveolens (L.) Poit. (Lamiaceae) is a perennial aromatic shrub widely naturalized in tropical and subtropical regions (Peerzada, 1997). Although often categorized as a ruderal or invasive species in agro-ecosystems, it produces dense, nectar-rich inflorescences that attract a diverse assemblage of bees (Raw, 2004). Its extended flowering phenology enhances temporal continuity of nectar resources, which is particularly valuable in semi-arid landscapes experiencing prolonged dry periods (Dafni, 1992). Recent studies emphasize the ecological importance of generalist flowering shrubs in sustaining bee populations within disturbed and semi-natural habitats (Shakoori & Salmanpour, 2024). Bee foraging behavior is governed by optimal foraging principles, whereby individuals maximize energetic returns while minimizing travel and handling costs (Pyke, 1984; Waser, 1986).

Foraging parameters- including visitation frequency, handling time, inter-floral movement, and patch fidelity are influenced by both floral rewards and environmental conditions. Temperature regulates flight muscle thermogenesis and metabolic performance (Heinrich, 1993). Moderate thermal conditions enhance foraging efficiency, whereas excessive heat suppresses midday activity (Herrera, 1990). Relative humidity influences nectar concentration and palatability (Pacini & Nepi, 2007), while wind velocity affects flight stability and energetic expenditure (Crall et al., 2017). Recent investigations indicate that climatic variability significantly affects pollinator occurrence patterns and spatial distribution (Rahimi & Jung, 2024). In semi-arid agro-ecosystems, pollination by honey bees has been shown to increase crop yield and quality, highlighting the applied significance of maintaining pollinator populations (Seddik & Ali, 2025). Furthermore, native bee conservation in arid ecosystems enhances biodiversity stability and ecosystem service delivery (Alarsan, 2025).

Pollination interactions form complex ecological networks composed of plant and pollinator species interconnected through visitation events (Memmott et al., 2004). Network redundancy and species diversity buffer ecosystems against species loss and environmental perturbations (Bascompte & Jordano, 2007). Conservation of semi-natural habitats within agricultural landscapes promotes pollinator spillover and maintains ecosystem services essential for both wild plant reproduction and crop productivity (Winfree et al., 2009; Garibaldi et al., 2013). Despite extensive global research, quantitative studies from the southern Aravalli hills remain scarce. The ecological roles of *H. suaveolens* as a nectar resource and its influence on bee diversity, visitation dynamics, and microclimatic sensitivity in Abu Road tehsil have not been systematically evaluated. Addressing this knowledge gap is critical for understanding pollination ecology under semi-arid climatic variability. The present study therefore integrates species-level documentation, behavioral ecology, and microclimatic analysis over a two-year period to provide comprehensive insight into plant–pollinator interactions in this ecologically significant region.

2. Materials and Methodology

The present study was conducted in Abu Road tehsil, located in Abu Road in the southern part of Rajasthan, forming part of the ecologically significant Aravalli Range. The region represents a semi-arid to sub-humid transitional zone with annual rainfall of approximately 600-800 mm, mean summer temperatures ranging from 30-42 °C, monsoonal relative humidity between 55-85%, and cooler winters occasionally dropping below 10 °C.

The study landscape comprised heterogeneous habitats including dry deciduous forest patches (dominated by *Anogeissus pendula, Boswellia serrata, Butea monosperma, Acacia catechu*), scrublands with *Prosopis juliflora* and *Ziziphus nummularia*, riverine tracts with *Tamarindus indica* and *Ficus religiosa*, and agricultural fields cultivating wheat (*Triticum aestivum*), mustard (*Brassica juncea*), maize (*Zea mays*), pearl millet (*Pennisetum glaucum*), castor (*Ricinus communis*), and cumin (*Cuminum cyminum*). The focal species *H. suaveolens* occurred abundantly in open scrub,

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forest margins, fallow lands, and roadsides. Materials used included entomological sweep nets (30–35 cm diameter), killing jars with ethyl acetate, insect pins and collection boxes, stereoscopic microscope, GPS device, digital thermometer, portable hygrometer, digital anemometer, Cannon DSLR camera with lens (70-300 mm), field data sheets, and statistical software for analysis.

Field investigations were carried out from April 2022 to June 2024 with regular monthly surveys, intensified during peak flowering of *H. suaveolens*. Permanent quadrats (10 m × 10 m) were established across forest edges, scrublands, agricultural margins, and riverine habitats. Standardized visual observations (10–15 minutes per quadrat) were conducted between 06:00 h and 18:00 h, with focused monitoring during peak foraging hours (08:00–11:00 h) to record species identity, visitation frequency (bees min^{-1}), foraging resource (nectar/pollen), handling time, and diurnal activity pattern. Sweep net sampling along 100 m transects was performed to collect representative specimens, which were euthanized using ethyl acetate, pinned, labeled (date, time, GPS coordinates, habitat, host plant), and identified using morphological taxonomic keys (Michener, 2007) under a stereoscopic microscope. High-resolution macro photography was used to document bee diversity and foraging behavior.

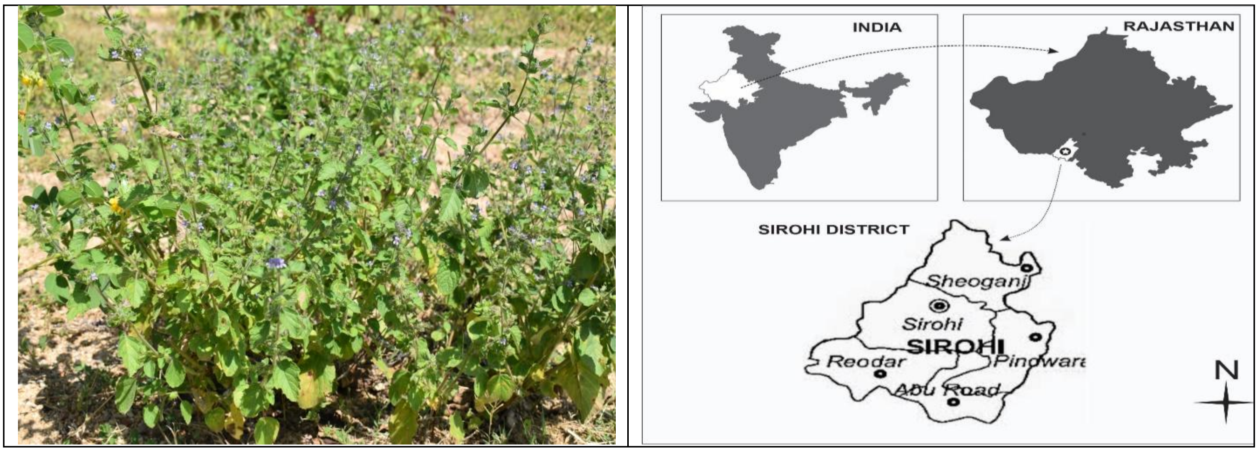

Figure 1: (a) Flowering plant of *H. suaveolens* observed in the study area; (b) geographic location of the study sites in Abu Road tehsil, Rajasthan, India

3. Results and Discussion

A total of 13 bee species belonging to three families (Apidae, Megachilidae, and Halictidae) were recorded foraging on *H. suaveolens* during the study period in Abu Road tehsil. The family Apidae was dominant, contributing 53.85% (7 species) of the total bee fauna recorded, followed by Megachilidae (30.77%; 4 species) and Halictidae (15.38%; 2 species). The dominance of apid bees indicates the suitability of *H. suaveolens* flowers for social and large-bodied bee species that are efficient nectar foragers. Among the observed species, *Apis dorsata, Apis florea*, and *Amegilla zonata* were the most frequent floral visitors and constituted the principal pollinators of the plant in the study area. The presence of both social and solitary bees reflects the heterogeneous habitat conditions surrounding the study sites, which provide suitable nesting substrates and continuous floral resources.

Seasonal variation in bee foraging activity was strongly influenced by microclimatic factors. The highest visitation rate was recorded in April (17 bees min^{-1}) under moderate temperature (30 °C), low relative humidity (26%), and moderate wind velocity (3.06 m s^{-1}). A gradual decline in foraging activity was observed during the monsoon months (June–August), coinciding with increasing humidity levels (55–84%) and relatively high wind velocities (4.39–4.72 m s^{-1}). The lowest visitation rate occurred in December (4 bees min^{-1}) when temperature dropped to 19 °C.

Table 1: Taxonomic composition of bee species recorded on *H. suaveolens* in Abu Road tehsil, Rajasthan

Sr. No.	Bees Species	Family (% contribution)	Order
1	*Apis dorsata* (Fabricius, 1793)	Apidae (53.85)	Hymenoptera
2	*Apis florea* (Fabricius, 1787)		
3	*Amegilla zonata* (Linnaeus, 1758)		
4	*Ceratina smaragdula* (Fabricius, 1787)		
5	*Tetragonula iridipennis (Smith, 1854)*		
6	*Thyreus ramosus* (Lepeletier, 1841)		
7	*Xylocopa fenestrata* (Fabricius, 1798)		
8	*Megachile albifrons* (Smith, 1853)	Megachilidae (30.77)	
9	*Megachile bicolor* (Fabricius, 1781)		
10	*Megachile gathela* (Cameron, 1908)		
11	*Megachile lanata* (Fabricius, 1775)		
12	*Nomia crassipes* (Fabricius, 1798)	Halictidae (15.38)	
13	*Nomia iridescens* (Smith, 1853)		

Table 2: Average Temperature, Relative Humidity and Wind Velocity with respect value of foraging rate from the study area

Month	Average Temperature (°C)	Relative Humidity (%)	Wind Velocity (m/s)	Foraging Rate (bee/minute)
April	30	26	3.06	17
May	33	37	4.44	11
June	30	55	4.72	9
July	29	78	4.39	7
August	28	84	3.58	5
September	27	74	2.69	7
October	26	47	2.33	12
November	22	44	2.11	5
December	19	47	1.78	4
January	17	46	2.22	6
February	20	37	2.78	7
March	27	28	2.78	11

Statistical analysis revealed that temperature exhibited a moderate positive correlation with bee activity ($r \approx +0.45$), indicating that warmer conditions generally promoted foraging. In contrast, relative humidity showed a strong negative correlation with visitation frequency ($r \approx -0.82$), suggesting that excessive atmospheric moisture may reduce bee flight activity and nectar concentration. Wind velocity also showed a negative relationship with foraging rate ($r \approx -0.63$), likely due to increased energetic costs of flight and reduced flight stability under windy conditions. The dominance of Apidae observed in the present study is consistent with findings reported from other semi-arid ecosystems where social bees constitute major floral visitors due to their large colony size and efficient recruitment systems (Abrol 2012; Garibaldi et al. 2013). Similar pollinator assemblages associated with Lamiaceae plants have been reported in Mediterranean ecosystems, where nectar-rich flowers attract a wide spectrum of bees including Apis, Amegilla, and Megachile species (Akka et al. 2025).

These results indicate that optimal foraging conditions for bees occurred under moderate temperature (26–30 °C), relatively low humidity (26–47%), and wind velocities around 2–3 m s^{-1}. Similar climatic influences on bee foraging activity have been documented in other semi-arid ecosystems, where abiotic factors significantly regulate pollinator behavior and plant–pollinator interactions. The extended flowering period and nectar availability of *H. suaveolens* make it an important seasonal resource for pollinators in semi-arid landscapes. Even though the species is sometimes considered a ruderal or invasive plant, its ecological role in sustaining pollinator communities may contribute to maintaining pollination services in fragmented habitats of the Aravalli region.

4. Conclusion

The present study provides a comprehensive assessment of bee diversity and foraging dynamics associated with *H. suaveolens* in the semi-arid landscape of Abu Road, Rajasthan. A total of 13 bee species belonging to three families were recorded, with Apidae representing the dominant group. The high frequency of visitation by *Apis dorsata, Apis florea*, and *Amegilla zonata* indicates that these species play a significant role in pollination of *H. suaveolens* in the region. Foraging activity exhibited clear seasonal patterns and was strongly influenced by microclimatic variables. Moderate temperatures and lower humidity favored increased bee activity, whereas high humidity and stronger winds reduced visitation rates. These findings demonstrate that climatic conditions act as key regulators of pollinator behaviour in semi-arid ecosystems.

The consistent utilization of *H. suaveolens* by diverse bee species highlights its ecological importance as a seasonal nectar resource. Preservation of semi-natural habitats containing wild flowering plants is therefore essential for sustaining pollinator populations and maintaining ecosystem services such as pollination. Further long-term studies integrating landscape ecology and pollinator network analysis are recommended to better understand the dynamics of plant–pollinator interactions in the Aravalli region.

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Fig 2. *Apis dorsata* (Fabricius, 1793)

Fig 3. *Apis florea* (Fabricius, 1787)

Fig 4. *Amegilla zonata* (Linnaeus, 1758)

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Fig 5. *Ceratina smaragdula* (Fabricius, 1787)

Fig 6. *Tetragonula iridipennis (Smith, 1854)*

Fig 7. *Thyreus ramosus* (Lepeletier, 1841)

Fig 8. *Xylocopa fenestrata* (Fabricius, 1798)

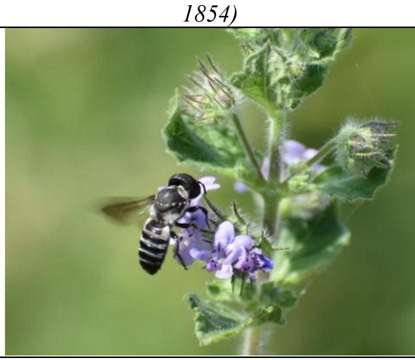

Fig 9. *Megachile albifrons* (Smith, 1853)

Fig 10. *Megachile bicolor* (Fabricius, 1781)

Fig 11. *Megachile gathela* (Cameron, 1908)

Fig 12. *Megachile lanata* (Fabricius, 1775)

Fig 13. *Nomia crassipes* (Fabricius, 1798)

Fig 14. *Nomia iridescens* (Smith, 1853)

Figure 2-14: Photographic documentation of bee species recorded visiting *H. suaveolens* in Abu Road tehsil, Rajasthan

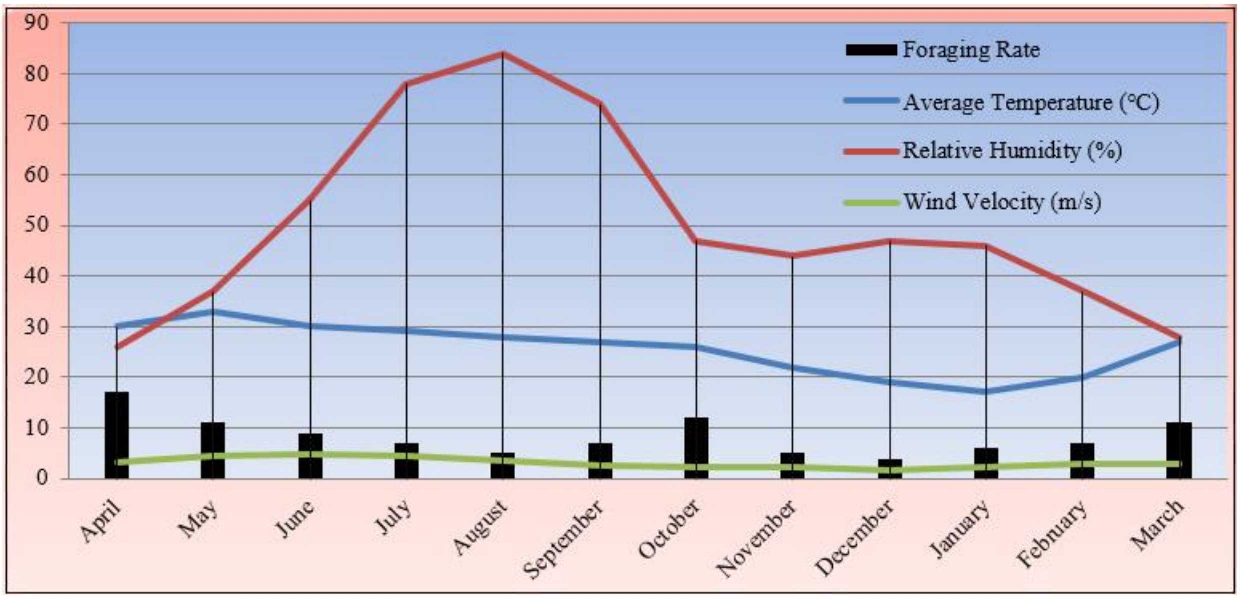

Figure 15: Relationship between climatic variables (temperature, relative humidity, and wind velocity) and bee foraging rate recorded in the study area.

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