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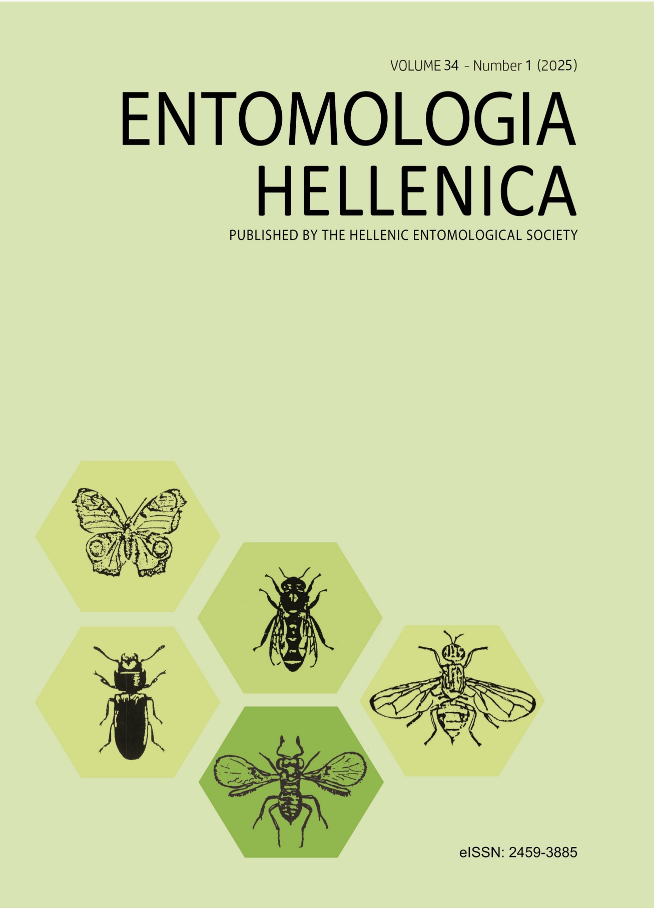

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DHARAM PAL ABROL

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Foraging activity of *Apis florea* Fabricius, 1787, an important pollinator of fennel, *Foeniculum vulgare* Mill.

DHARAM P. ABROL

Faculty of Agriculture, Sher-e-Kashmir University of Agricultural Sciences and Technology, Jammu, Main Campus Chatha, Jammu-180009

ABSTRACT

The foraging behaviour of fennel (*Foeniculum vulgare* Mill.) flower visitor insects was studied in relation to five environmental variables. Observations on insect species were made during February-March at weekly intervals throughout the flowering period. Hourly counts on individual visitors were made at the beginning of each hour, from commencement to cessation of daily activities. Among 21 visitor species, the dwarf honeybee (*Apis florea*) was the most abundant, accounting for more than 92.69 % of total visitors. Flight activity commenced when environmental variables surpassed a minimum threshold, while it ceased primarily due to a decline in light intensity and radiation. The foraging population showed a significant and positive correlation with air temperature, light intensity, solar radiation, and sugar concentration of nectar, and a negative correlation with relative humidity. However, path coefficient analysis revealed that the direct effect of solar radiation was high and positive, followed by air temperature and light intensity, while the direct effect of relative humidity was low and negative. The direct effect of sugar concentration of nectar was positive and negligible. Path coefficient analysis provided a clearer understanding of the effects compared to simple correlation analysis. On average, *A. florea* visited 7.31 ± 0.73 umbels and 19.13 ± 0.39 flowers per minute during various hours of the day. The plots pollinated by insects produced significantly more seeds with heavier weight compared to those isolated from insect visits. Fennel flowers exhibited a bimodal pattern of nectar secretion. Evidently, insect pollination needs to be encouraged for quality and quantity of seed production.

KEY WORDS: Insect pollinators, fennel, pollination, environmental factors, seed production, path analysis.

Introduction

Fennel is an important seed crop with umbelliferous hermaphrodite flowers, characterized by protandry that requires cross pollination. It is widely cultivated throughout the temperate and subtropical regions of the world and major growing countries are India, Syria, Egypt, Turkey, Germany, Spain and Pakistan. Fennel is promiscuous but, although it is not adapted to a specialised pollinator, honeybees are the most common foragers and therefore its major pollinators (Chaudhry, 1961; Bell, 1971; Giudici, 1991). If bees are absent, other insects, mainly from the order Diptera, take over this role (Giudici, 1991).

Fennel has compound umbels of yellow flowers producing copious nectar with very high concentration of sugars (Curtis, 1963; Bell, 1971; Giudici, 1991). It is protandrous and flower maturity progresses in waves, with the outer umbellules maturing first (Sundararaj et al., 1963). These waves of maturity are continued between the umbel orders with the primary umbel maturing

*Corresponding author: dharam_abrol@rediffmail.com

first, followed by the secondaries, tertiaries and so forth (Bell, 1971).

In each fennel umbellule and in each umbel, flowers at the periphery open first and those in the center last. The five stamens emerge sequentially over a 6–8-hour period although this depends on the variety. When the stigma is prominent and the styles are long, they are exposed to the bud, before the flowers open (Sundararaj et al., 1963). In carrots, there is some possibility for self-pollination within umbels since the first stigmas become receptive before the last anthers dehisce (Hawthorn et al., 1960). This may also occur in fennel, depending on the strength of the protandry.

It is suggested that bees are particularly good cross pollinators because they land first and then move across the flower to the source of the floral reward. It is likely that bees would land on the outside umbellules first and then crawl inwards, pollinating the outer flowers with non-self-pollen before reaching the floral reward of the inner flowers. The pollination ecology of fennel shows adaptations to many vectors, but in particular to bees and wind. Pillai and Nambiar (1982) found that fennel is highly cross pollinated with both wind and bees as vectors.

Of the insect visitors to a crop in Pusa, India, Narayanan et al. (1960) noted 88.4% belonged to the genus Apis, principally to the species *A. florea* (81.5%), the smallest of the three Apis species detected. Other visitor species belong to the order Diptera. *Apis florea* visits continued for longer during the day than those by the larger bee species, giving rise to the hypothesis that fennel did not provide sufficient floral reward to remain attractive to the larger species for long. Visits by larger species stopped after 11.00 am, while the number of visits by the smaller *A. florea* increased until 1.00 pm (Narayanan et al., 1960). Baswana (1984) recorded many different insects visiting a fennel crop in Hisar, India. The main visitors were *A. florea* and *Apis dorsata* Fabricius. Peak activity was between 11.00 am and 2.00 pm during the flowering season. It is suggested that temperatures during this time are more favourable for both insect activity and for anthesis and nectar secretion.

Giudici (1991) found that *Apis mellifera* L. was the dominant species, comprising 80-85% of the visitors to fennel flowers. Other species have also been reported to be effective pollinators by Giudici (1991), although they were present in small numbers, such as native bees and various moths and butterflies. This gives credibility to the earlier hypothesis that fennel has many characteristics, which make it compatible with a multitude of vectors. Some members of the order Coleoptera were also reported to be pollinators by Giudici (1991) although not as effective as the Hymenoptera, Diptera or Lepidoptera. Giudici (1991) studied pollination in fennel using cages to exclude various sized insect species from secondary umbels. Perforated cellophane bags reduced seed-set to 7%, while a cage excluding honeybees maintained a seed set of 66%. Unfortunately, no estimate of seed set for uncaged umbels was reported. The seed-set decline was attributed to the exclusion of pollinators.

A holistic approach to fennel crop production is required to pinpoint the problem before a solution can be sought. Nectar production in fennel is abundant and the nectar is very concentrated being up to 65% sugar (Giudici, 1991). Bees will not gather nectar which is too diluted because transport requires more energy expenditure than is gained. Therefore, concentrated nectar is an asset to a plant as an attraction to bees. Giudici (1991) suggests that fennel nectar may become so concentrated and sticky that bees may avoid the crop.

Fennel shows no special arrangement of perianth consistent with attracting one particular insect species. However, the umbels are terminal and therefore are observable to insects flying above. They form a flat surface consistent with butterfly and moth pollinated flowers. The petals of fennel flowers are both conspicuous and attractive, early in flowering, indicating insect pollination. The lack of landing platforms on individual flowers helps support the hypothesis that fennel is promiscuous and not adapted specifically to bees.

Bharti et al. (2015) reported that twenty-five insect species of five orders and fifteen families were recorded from fennel flowers, in which, seven belonged to order Lepidoptera, nine to Hymenoptera, five to Diptera, three to Coleoptera and one to Odonata. Klein et al. (2007) categorized fennel as a highly insect-dependent crop (40-90%) for seed production. Additionally, insect pollination has been shown to directly enhance fennel seed set (Chaudhary, 2006; Kumar and Singh, 2017b; Meena et al., 2015) and is linked to essential oil production (Schurr et al., 2021). For instance, Chaudhary et al. (2006) reported an 82% decrease in seed weight per plant in the absence of insect pollination compared to insect-assisted pollination. However, there is a lack of studies investigating the extent of insect dependence for fennel reproduction, particularly in field settings with high insect diversity. More research is needed to better understand the fennel reproductive system in real crop fields. To sustainably support fennel production, it is crucial to comprehend and quantify the role of insect pollination in fennel reproduction, especially considering the protandry of the species. Thus, the present study is a first step to better understanding the relative contributions of the different species of pollinators to crop pollination and yield depending on the degree of autogamy and reliance on insect pollination on plant species (Klein et al. 2007; Schurr et al. 2021), foraging activity (visitors vs. pollinators; Ollerton, 2017), and the quantity and quality of pollen transported or deposited. It is also essential to analyze this relative contribution with regard to the landscape and local contexts, the production practices, and the context of climate change.

Apart from physical flower features such as color, shape, odor, and potassium content of nectar (Waller et al., 1972; Hagler 1990), the diversity of environmental factors such as temperature, humidity, light, solar radiation, time of the day and nectar flow decisively shapes the behavior of pollinating insects, thereby influencing the cross-pollination and the production of the crop (Vischer and Seeley, 1982; Corbet et al., 1993, Mohanty et al 2023, Clarke and Robert 2018, Czekońsk et al 2023, Usha et al 2020, Karbassioon et al 2023, Lee et al 2018, Reddy et al 2015). The present study was, therefore, conducted to determine the diversity and abundance of pollinating insects, their foraging ecology and their role in seed production.

Materials and Methods

Study site: The study was conducted from February to March 2014 at the Research Farm of the University of Agricultural Sciences and Technology in Jammu, India (320 39’ 13’’ N latitude 740 48’ 16’’ °E longitude, 300 m asl). The climate of the area is typically subtropical with 1130 mm annual rainfall. The crop was grown as per recommended package of practices of the University (SKUAST Jammu, 2007) using a seed rate of 3 - 4 kg/ha. Seedlings, 5 - 6 weeks old, were transplanted at 60 x 30 cm distance. The crop was cultivated in a randomized block design (RBD) with three replications, and data on insect pollinators visiting fennel umbels were collected. The abundance and diversity of insect visitors to the fennel flowers, foraging ecology and impact on seed production was studied. Observations were made at weekly intervals throughout the flowering season, from the last week of February to the third week of March. For each weekly observation, insect counts were made hourly at the beginning of each hour, from commencement of activity at dawn, until the end of activity at dusk, for each observation day. Five 1 x 1 m^2 plots were marked and insects were recorded by visual counting from each side of the plot, for a duration of one minute, every hour, from 9:00 to 17:00 hours (Abrol, 1991). Simultaneously, air temperature and relative humidity were recorded with a dry and wet bulb thermometer kept in the shade, while solar radiation was recorded with a solarimeter (luxomet-300) and light intensity with a luxmeter (luxomet-300) at a height of 50 cm above ground. Total dissolved solids in nectar were estimated using a pocket refractometer (Erma; Japan). Nectar was collected from the crop of foraging bees. For this purpose, the foraging bees were captured and their crop pressed. As the drop of nectar oozed out of their mouth, the nectar was transferred to the refractometer to be evaluated.

Impact of insect visitors on seed production: The role of insect pollination on the quality and quantity of fruit production was evaluated using open pollination and self-pollination. For this purpose, a specific number of plants was enclosed in pollination cages 5×3 meters, and an equal number of plants were left for open pollination. On maturity, the flowers were harvested from both treatments and compared for quantity and physicochemical characteristics which included mean number of flower/umbel, mean number of filled seed/umbel, percent of seed set and 1000-seed weight (g). The recorded data were analysed for their variation between different treatments using the Statistical Package for the Social Science (SPSS) and O.P Stat.

Data analysis: The pollinator diversity was calculated using the Shannon diversity index (Shannon and Weaver 1949, Magurran, 2004) given by the formula:

$$H=-\sum[(pi)\times\log(pi)]$$

where:

H- Shannon diversity index

pi - proportion of individuals of i-th species in a whole community

∑ - sum

log - the natural logarithm, but the base of the logarithm is arbitrary (10 and 2 based logarithms are also used).

pi=nN

n - individuals of a given type/species

N - total number of individuals in a community.

Path analysis: Data was analysed for simple correlations using the method of least squares (Sokal and Rholf, 1981). If the bee activity was found to be linearly related to a factor (a condition specified by Li, 1956 for path coefficient analysis) the data was analysed further using a path coefficient technique. The method involves the partitioning of correlation coefficients into components of direct and indirect effects (via uni-directional pathways) and indirect effect through alternate pathways [pathways (P) x correlation coefficient (r)]. Bee activity was considered as a resultant (dependent) variable and temperature, relative humidity, light intensity, solar radiation and sugar concentration of nectar as causal (independent) variables. Both coefficients were obtained by solving simultaneous equations by the method of least squares (Li, 1956; Dewey and Lu, 1959; Mitchell, 1992; Scheiner et al., 2000). The impact of insect pollinators on seed production was assessed by enclosing the plots in muslin cages, with equal number of plots left for open pollination. After harvesting, seed yield was compared in both treatments. The recorded data were analysed following Sokal and Rholf (1981).

Results

The observations of insect species visitors to fennel flowers revealed a rich faunal diversity (Table 1), including 21 species belonging to 17 genera of 12 families and 4 orders. Among all insect visitors, Apis florea was the major pollinator accounting for more than 92.6% of the total flower visitors. Other insect species observed in low numbers at interrupted hour intervals included the honeybees *A. dorsata*, *A. cerana*, *A. mellifera*, the carpenter bee *Xylocopa fenestrata*, *Camponotus compressus*, *Halictus* sp. *Lasioglossum* sp., *Polistes hebreaus*, *Episyrphus balteatus*, *Eristalis tenax*, *Ischodion scutellaris*, *Musca domestica*, *Sarcophaga* sp., *Chrysomia megacephala*, *Metasyrphus corolla*, *Coccinella septumpunctata*, *Coccinella* sp., *Pieris brassicae*, *Danis chrysippus*, *Genepterynx hemmi* and *Aulacophora foveicollis*.

TABLE 1: Insect visitors and their percentage proportion on *Foeniculum vulgare* flowers

No.	Insect species	Family	Order	Percentage Proportion
1.	*Apis florea*	Apidae	Hymenoptera	92.6
2.	*Apis dorsata*	Apidae	Hymenoptera	0.50
3.	*Apis mellifera*	Apidae	Hymenoptera	1.34
4.	*Apis cerana*	Apidae	Hymenoptera	0.53
5.	*Xylocopa fenestrata*	Apidae	Hymenoptera	0.12
6.	*Camponotus compressus*	Formicidae	Hymenoptera	0.74
7.	*Halictus* sp.	Halictidae	Hymenoptera	0.06
8.	*Lasioglossum* sp.	Halictidae	Hymenoptera	0.08
9.	*Polistes hebreaus*	Vespidae	Hymenoptera	0.04
10.	*Episyrphus balteatus*	Syrphidae	Diptera	0.13
11.	*Eristalis tenax*	Syrphidae	Diptera	1.90
12	*Ischodion scutellaris*	Syrphidae	Diptera	0.16
12.	*Musca domestica*	Muscidae	Diptera	0.13
13.	*Sarcophaga* sp.	Sarcophagidae	Diptera	0.17
14.	*Chrysomia megacephala*	Calliphoridae	Diptera	0.22
15.	*Metasyrphus corolla*	Syrphidae	Diptera	0.23
16.	*Coccinella septempunctata*	Coccinellidae	Coleoptera	0.11
17.	*Coccinella* sp.	Coccinellidae	Coleoptera	0.17
18.	*Pieris brassicae*	Pieridae	Lepidoptera	0.21
19.	*Danis chrysippus*	Danaidae	Lepidoptera	0.11
20.	*Genepterynx hemmi*	Pieridae	Lepidoptera	0.23
21.	*Aulacophora foveicollis*	Chrysomelidae	Coleoptera	0.22
Total				**100.00**

Note
Species composition is generally expressed as a percentage, so that all species add up to 100%. Composition was calculated using density as a measure.

The Shannon Diversity Index (H') was used as a measure to quantify the diversity of a community, incorporating both species richness (number of species) and evenness (relative abundance of each species). A higher value indicates greater diversity.

The value of H' = 0.2287 indicated that species diversity was low (Table 2). This indicates that the community was either dominated by a single species (low evenness) or has very few species (low richness). The closest the value is to zero, the less diverse the community is. In comparison, higher Shannon Index values (e.g., 2–4) typically indicate more complex and diverse ecosystems.

TABLE 2: Diversity of insects as calculated using the Shannon Diversity Index (H')

No.	Insect species	Total individuals (n)	pi	logpi	pi(logpi)	
1.	*Apis florea*	462	0.909037	-0.04142	-0.03765	
2.	*Apis dorsata*	2.5	0.004919	-2.30812	-0.01135	
3.	*Apis mellifera*	6.7	0.013183	-1.87999	-0.02478	
4.	*Apis cerana*	2.65	0.005214	-2.28281	-0.0119	
5.	*Xylocopa fenestrata*	0.6	0.001181	-2.92791	-0.00346	
6.	*Camponotus compressus*	3.7	0.00728	-2.13786	-0.01556	
7.	*Halictus* sp.	0.03	5.9E-05	-4.22894	-0.00025	
8.	*Lasioglossum* sp.	0.4	0.000787	-3.104	-0.00244	
9.	*Polistes hebreaus*	0.2	0.000394	-3.40503	-0.00134	
10.	*Episyrphus balteatus*	9.65	0.018987	-1.72153	-0.03269	
11.	*Eristalis tenax*	9.5	0.018692	-1.72834	-0.03231	
12.	*Ischodion scutellaris*	0.8	0.001574	-2.80297	-0.00441	
13.	*Musca domestica*	0.65	0.001279	-2.89315	-0.0037	
14.	*Sarcophaga* sp	0.85	0.001672	-2.77664	-0.00464	
15.	*Chrysomia megacephala*	1.1	0.002164	-2.66467	-0.00577	
16.	*Metasyrphus corolla*	1.15	0.002263	-2.64536	-0.00599	
17.	*Coccinella septumpunctata*	0.55	0.001082	-2.9657	-0.00321	
18.	*Coccinella* sp.	0.85	0.001672	-2.77664	-0.00464	
19.	*Pieris brassicae*	1.05	0.002066	-2.68487	-0.00555	
20.	*Danis chrysippus*	0.55	0.001082	-2.9657	-0.00321	
21.	*Genepterynx hemmi*	1.65	0.003247	-2.48858	-0.00808	
22.	*Aulacophora foveicollis*	1.1	0.002164	-2.66467	-0.00577	
	H'	508.23			-0.2287	0.2287

Of all species, the dwarf honeybee *A. florea* was the most common, accounting for more than 92.6 % of the total flower visitors, so detailed observations were made on its foraging behaviour.

Using Density Data

% composition of species A = (number of individuals of species A / total number of individuals) x100.

Commencement and cessation of foraging activities

Flight activities of *A. florea* commenced between 09.00 to 09.30 am, when the temperature ranged between 16.5 and 18.5oC, relative humidity was between 65.0 – 85.0 %, light intensity at 4700- 6800 lx and solar radiation at 70.0 – 87.0 mW/cm^2. Cessation of activities was governed mainly by a decline in the values of light intensity (1300 - 1700 lx) and solar radiation (21 - 33 mW/cm^2).

Figure 1 shows that *A. florea* activity followed air temperature, light intensity, solar radiation and sugar concentration of nectar but was inversely related to relative humidity. The peak foraging population of *A. florea* occurred between 12:00 and 14:00 h, with air temperatures ranging from 18.5 to 22.5°C, relative humidity between 44% and 74%, light intensity from 4400 to 9700 lx, solar radiation between 48 and 96 mW/cm², and sugar concentration of nectar between 47% and 55%.

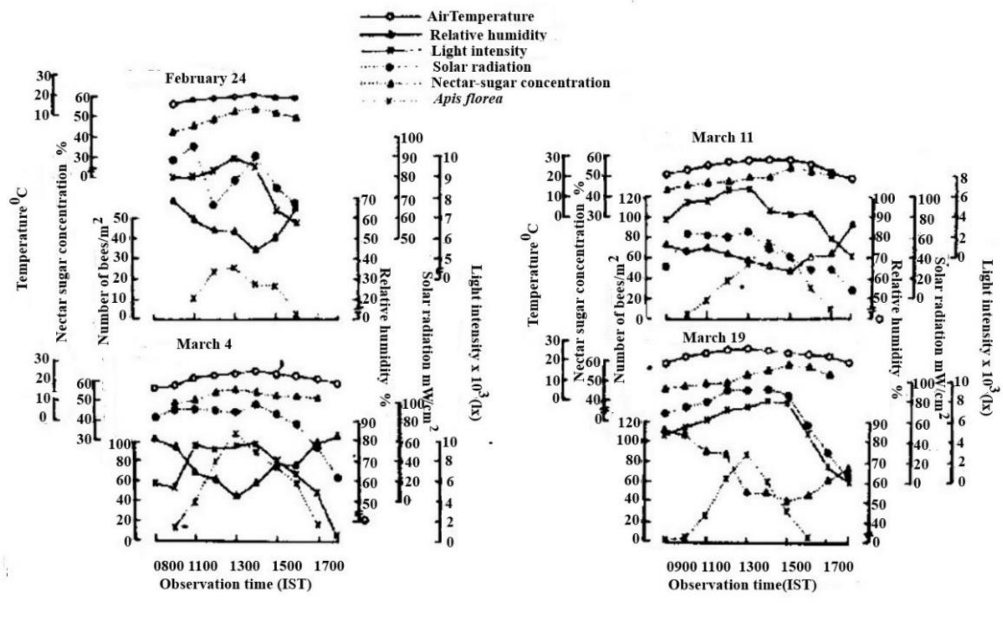

FIG. 1: Diurnal pattern of activity of *Apis florea* on *Foeniculum vulgare* in relation to temperature, relative humidity, light intensity, solar radiation and sugar concentration of nectar.

After that, bee populations declined and at 17:00 h, only 0.40 bees / umbel / min were observed. Bee abundance followed air temperature, light intensity but was inversely related to relative humidity. However, diurnal variations in solar radiation and fluctuations in sugar concentration of nectar were not found to be significantly associated with the changes in field populations of *A. florea*. A Correlation Matrix (Table 3) between bee activity and the different environmental factors indicated a highly significant and negative association of bee activity with relative humidity, with the remaining environmental variables being highly significant and positive. The interrelationships between independent variables were often highly significant. There was therefore a need for further analysis by the Path Coefficient technique to ascertain the more important factors influencing bee flight activity.

TABLE 3: Correlation matrix exhibiting the relationship of bee activity (*Apis florea*), environmental factors and interrelationships of these factors. * P < 0.05; ** P < 0.01; ns= non-significant; df = n-2 = 68.

Coefficient of correlation (r) with					
Factors	*Apis florea*	Relative humidity (%)	Light intensity (lx)	Solar radiation (mW/cm^2)	Sugar concentration of nectar (%)
Temperature	0.653**	- 0.354*	1.00	0.0397	0.155ns
Relative humidity	-0.420*	-0.542*	0.0940 ns	-0.143ns	
Light intensity	0.509*	0.0786ns	0.0294 ns		
Solar radiation	0.185ns	0.967**			
Sugar concentration of nectar	0.177ns				

* P < 0.05; ** P < 0.01; ns= non-significant; df = n-2 = 68.

Table 4 shows the direct and indirect effects of the various environmental factors on the flight activity of *A. florea*. The direct effect of temperature was highly pronounced and positive (0.6981). The overall significant positive association of temperature (r = 0.653) with bee visits was largely a reflection of positive inputs of light intensity and solar radiation. The simple correlation between bee visits and relative humidity was significantly high and negative (r = -0.420) resulting largely from its negative interactions with temperature. The direct effect of light intensity was positive (0.3393).

The overall positive influence of light intensity on bee visits was largely a reflection of positive inputs of solar radiation. The total correlation between bee visits and solar radiation was positive (r = 0.185), resulting mainly from the positive direct effect of solar radiation itself (0.8674) and the positive indirect effect of temperature (0.0277) and light intensity (0.0266). The direct effect of sugar concentration of nectar (-0.7381) on bee visits was negative. The total significant correlation coefficient between bee visits and sugar concentration of nectar (r = 0.177) was strengthened by high positive indirect effect via light intensity and solar radiation.

An overall analysis of direct and indirect effects of various environmental factors on bee activity therefore reveals that temperature, light intensity and solar radiation were the three most important factors which exerted a pronounced and positive direct effect while relative humidity had negative and negligible direct effect and the direct effect of sugar concentration of nectar was negative (Figure 2).

TABLE 4: Direct and indirect effects of environmental factors on flight activity of *Apis florea* F. (Bold lettering denote direct effects).

Pathways of association	Temperature	Relative humidity (%)	Light intensity (lx)	Solar radiation (mW/cm^2)	Sugar concentration of nectar (%)	correlation with bee activity (r)
Temperature	**0.6981**	0.0060	0.0339	0.0334	-0.1188	0.653
Relative humidity	-0.2471	**-0.0171**	-0.1841	-0.0815	0.1092	-0.420
Light intensity	0.0698	0.0093	**0.3393**	0.0681	0.0224	0.509
Solar radiation	0.0277	0.0016	0.0266	**0.8674**	-0.7381	0.185
Sugar concentration of nectar	0.1088	0.0024	-0.0099	0.8674	**-0.7381**	0.177

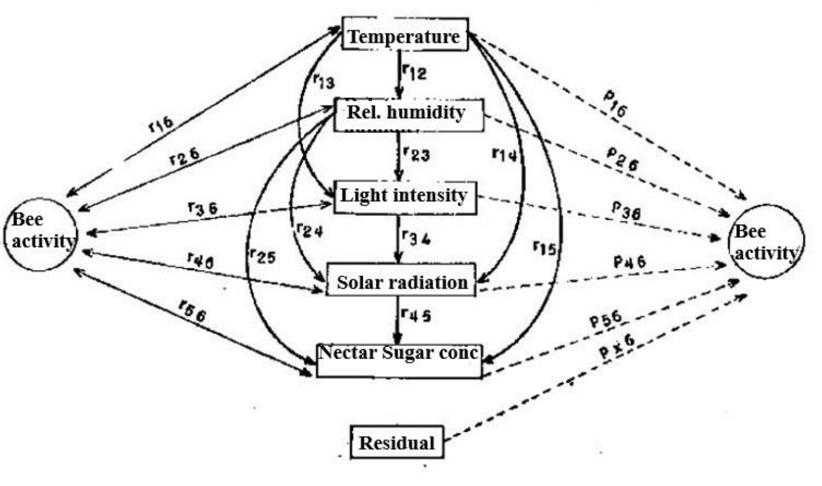

FIG. 2: A schematic model exhibiting interrelationship and direct effect of environmental factors like temperature, relative humidity, light intensity, solar radiation and sugar concentration of nectar, where r1-r5 are regression coefficient of bees with environmental variables and p1-p6 are path coefficients.

The relationship of different environmental factors and sugar concentration of nectar on bee activity successfully complementing pollination is shown in Figure 3. The schematic model shows how different factors influence each other to influence foraging by bees.

Foraging rates and impact of insect pollination on seed production

In general, *A. florea* visited fewer flowers / umbels during the early and late parts of the day (Table 5), the most being visited between 12.00 and 14.00 h. On average, 19.13 flowers / min were visited (range: 12.01 to 27.69), and an average of 7.31

umbels / min (range: 5.57 – 9.00). Table 6 shows that open umbels had significantly higher seed set than those excluded from insect visits (76.99 % vs. 55.52%). The number of filled seeds produced per umbel also varied significantly (209.66 vs. 100.23 seeds / capsule; P< 0.01), as did seed weight/umbel and 1000-seed weight. Mean number of flower/ umbels, mean number of filled seed/umbel, per cent seed set and 1000-seed weight (g) was significantly higher in open pollinated as compared to caged without insect pollinators.

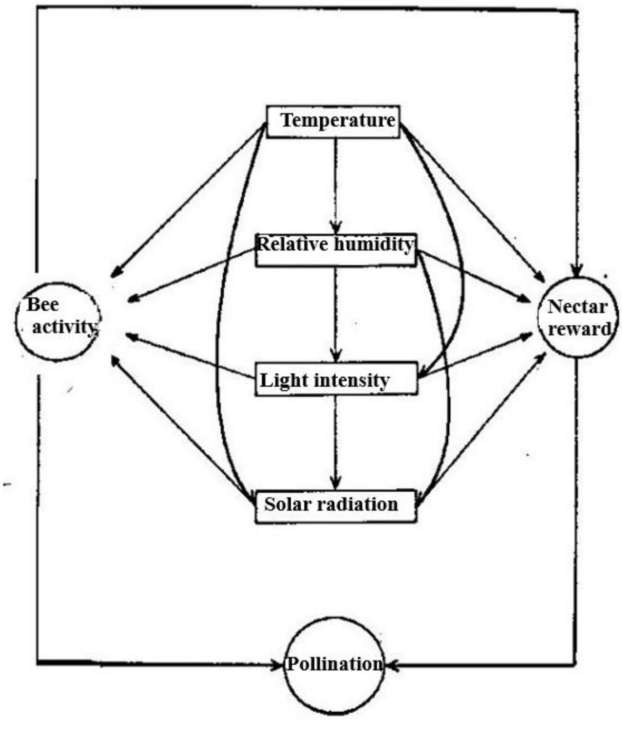

FIG. 3: A schematic model exhibiting the effect of different environmental factors on the caloric rewards vis-à-vis pollination activity of bees complementing successful pollination.

TABLE 5: Flower visitation rates of *Apis florea* on *Foeniculum vulgare* flowers. Each value is a mean ± S.D of 40 observations

Hour of observation (h)	Flowers visited/min	Umbels visited/min
10:00	12,01±1.47	7.67±0.65
11:00	26.94±0.75	5.77±0.65
12:00	23.14±4.37	8.00±0.54
13:00	27.69±3.49	6.00±0.98
14:00	16.71±2.44	9.00±0.89
15:00	16.10±1,06	8.74±0.55
16:00	16.74±1.25	6.23±0.82
17:00	13.77±2.14	7.12±0.76
Mean±S.D	19.13±0.39	7.31±0.73

TABLE 6: Effect of different modes of pollination on yield attributing characters of fennel.

Yield attributing characters					
Treatments	Modes of pollination	Mean number of flower/ umbels*	Mean number of filled seed/umbel*	Per cent seed set	1000-seed weight (g)
T1	Caged without insect pollinators (SP)	180.50	100.23	55.52	5.10
T2	Open to all insect pollinators (OP)	272.30	209.66	76.99	6.50
S. Em. (±)		0.184	0.298	1.371	0.088
C.D. (P = 0.05)		0.722	1.168	5.382	0.352

*Significance at 5%

Discussion

Fennel (F. vulgare) flowers attract a wide variety of insects of the orders Hymenoptera, Lepidoptera and Coleoptera, as has already been reported in earlier studies (Lederhouse et al., 1968; Free, 1993; Abrol, 1998; Bohart et al., 1970; Caron et al., 1975). In India, the bees *Apis cerana*, *A. dorsata*, *A. florea* and *Tetragoniula iridipennis* Smith account for more than 70% (Singh and Dharamwal, Dharmwal 1970), 95% (Jadhav, 1981), and 96% (Rao and Suryanarayana, 1989) of fennel flower visitors. Our studies showed that the dwarf honeybee *A. florea* was the most predominant, in accordance with Priti (1998) who also reported *A. florea* as the most abundant, followed by *A. mellifera* under low land conditions.

The commencement of flight activity of *A. florea* depended upon the attainment of minimum threshold environmental conditions, and cessation coincided with a decline in light intensity and solar radiation. Abrol and Kapil (1986) made similar observations on Megachile species. For other species of honeybees, i.e. *A. mellifera* and *A. cerana*, air temperature acted as a stimulus for the initiation of flight activities while the cessation was controlled by a decline in light intensity and solar radiation (Abrol, 1998). Osgood (1974) found that ambient temperature was the predominant factor in initiating morning flight activity of *Megachile rotundata* Fabricius while cessation was governed by decline in light intensity.

A maximum foraging population of *A. florea* was observed between 12.00 and 14.00 h when the air temperature ranged between 18.5 - 22.5 ºC and declined at higher temperatures. Similar observations were made by Free (1993) who found that metabolic activity of insects increases with temperature, so they visit more flowers. The daily visitation pattern showed that bee activity followed the overall trends of temperature, light intensity, solar radiation, and sugar concentration of nectar, yet it exhibited an inverse correlation with relative humidity.

The simple correlations revealed that bee activity correlated significantly and positively with temperature, light intensity and negatively with relative humidity. However, though positive but was not significantly associated with solar radiation and sugar concentration of nectar. Figure 2 shows how different factors directly or indirectly influence the bee activity.

Similar results have been reported by several earlier investigators (Lerer et al., 1992; Burill and Dietz, 1982; Nunez, 1977, Usha et al 2020, Karbassioon et al 2023, Lee et al 2018, Reddy et al 2025). Further examination of the Correlation Matrix revealed that environmental factors are also interrelated among themselves, suggesting that the influence expressed by simple correlations may not be direct. Path Analysis gave a different pattern of effects than that shown by simple correlation analysis, revealing that temperature, light intensity and solar radiation directly influenced the activity of *A. florea*. The strongly positive direct effect of these three factors on flight activity of *A. florea* is explained by the fact that all these three factors are interrelated and depend upon each other. Temperature and solar radiation are responsible for heating of the atmosphere and light intensity for illumination. The direct effect of relative humidity was low in magnitude and negative, probably due to the fact that relative humidity serves to balance the effects of the above three factors. The direct effect of sugar concentration of nectar was negative, showing that although it is an important factor for which the bees have to fly (Corbet, 1978), and under controlled conditions its effect will be reflected in appreciable proportions, under field conditions it also gets influenced by simultaneously operating other factors as the bee's activity itself, because nectar content is also influenced by increasing temperature and decreasing humidity (i.e., at high temperature and low humidity it gets concentrated and vice versa). The availability of nectar in flowers decisively shapes the behaviour of flower visitors (Heinrich, 1975; Abrol, 1992). Reward systems developed by flowers enable pollinators to discriminate between closely related plant species or ecotypes. *Apis florea* has been reported to have a close correlation between its tongue length and the corolla length of onion flowers, resulting in a co-partnership between the flowers and their pollen vectors (Abrol, 2010, Ali et al 2022). Coevolution has brought a close correlation between pollinator needs and floral energy expenditures (Heinrich, 1975), and the present work shows that the major variation in foraging activity (80.3%) is associated with the environmental factors examined here, while the remaining variation may be related to atmospheric pressure, wind velocity, caloric reward or unknown factors.

Apis florea visited 7.31 (5.57-9.00) - 19.13 (12.01 27.69) flowers/min, probably due to this suitability between tongue length and corolla length of fennel flowers. Earlier, Rao and Lazar (1980) reported that *A. cerana indica* was a faster flier than *A. florea* between onion umbels, visiting respectively 1.93 and 1.34 umbels per min, but on an individual umbel, *A. florea* showed a better foraging rate than *A. cerana* indica, visiting 6.53 and 5.93 flowers per min, respectively. Rao and Suryanarayana (1989) recorded *A. cerana*, *A.* florea and *T. iridipennis* visiting 2.3, 1.3 and 1.3 umbels per minute and 5.9, 6.5, and 2.5 flowers per minute. Priti (1998) reported that A. florea visited 5.71 flowers for simultaneous collection of nectar and pollen, and 6.03 for collection of pollen alone. Chandel et al. (2004) found that under the sub-temperate conditions of Himachal Pradesh, India (1200 m above mean sea level), A. dorsata proved to be the dominant visitor and the most efficient pollinator covering on average 7.5 flowers / umbel / visit during the peak hours of their foraging activity (12.00 - 14.00 h) compared with *A. cerana* and *A. florea* (5.4 and 3.2 flowers / umbel / visit).

Flower visitation rates may differ at different times of the day depending on atmospheric conditions, availability of nectar, pollen and bee species involved. Pollinating insects show varying preferences among different cultivars. This study shows that *A. florea* is the most efficient pollinator because of its capacity to work at high temperatures, maximum abundance, maximum foraging rates and duration of activity period. Whilst collecting nectar or pollen, *A. florea* also lies across the umbel, pollinating a large number of flowers. Earlier studies have also recognised *A. florea* as one of the most important pollinators of sarson (*Brassica campestris* L. var. sarson), toria (*Br. campestris* L. var. toria), raya (Br. juncea Czern & Coss), lucerne, onion and cultivated Apiaceae that include ajwan, anise, carrot, cumin, dill seed and fennel in the hot and dry agricultural plains of India (Sihag, 1986; Abrol, 2006). The present study also showed that insect pollinated plots produced significantly more seeds with heavier weights than those isolated from insect visits. Previously, Klein et al. (2007) categorized fennel as highly dependent on insects (40-90%) for seed production. Additionally, insect pollination has been demonstrated to significantly enhance fennel seed set (Chaudhary, 2006; Kumar and Singh, 2017b; Meena et al., 2015) and is associated with increased production of essential oils (Schurr et al., 2021). For instance, Chaudhary et al. (2006) observed an 82% decrease in seed weight per plant in the absence of insect pollination compared to pollinated plants. Insect-pollinated flowers also exhibited a higher number of fruits and greater amounts of anethole per hectare compared to bagged flowers (Schurr et al., 2019). However, studies investigating the extent of fennel's reliance on insects for reproduction remain limited, especially field studies encompassing a diverse range of insect species. Further research is necessary to deepen our understanding of the reproductive dynamics of fennel in actual agricultural settings. Similar findings were previously reported by Rao and Lazar (1983) for onions, where fruit setting was recorded at 93.5% with 3.6 g of seeds per umbel with pollinators, compared to 9.8% and 0.3 g without. Seed yields were higher in open-pollinated fields than in controlled environments (Orlova et al., 1981; Sihag, 1985). Kumar et al. (1985) also found greater set and yield and better seed germination from plots caged with bees, than from plots caged without bees or open plots, and more honeybees caused more seed set (Kubisova et al., 1986).

The flowers exhibited a bimodal pattern of nectar secretion and also varied in the sugar concentration of nectar and the number of caloric rewards produced during different hours of the day. In earlier studies also, bimodal pattern of nectar production has been reported (Vidal et al 2006, Cavalcante et al 2018).

In view of the importance of *A. florea* as a pollinator of fennel seed production, it is suggested that this bee species needs to be conserved and protected from the indiscriminate use of pesticides in order to produce good quality and quantity of fennel seed, as well as a wide variety of other crops for which it has been reported as acknowledged pollinator (Sihag, 1986).

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Μελέτη της συμπεριφοράς κατά την αναζήτηση τροφής από το *Apis florea* Fabricius, 1787, ενός σημαντικού επικονιαστή του μάραθου

DHARAM P. ABROL

Faculty of Agriculture, Sher-e-Kashmir University of Agricultural Sciences and Technology, Jammu, Main Campus Chatha, Jammu-180009

ΠΕΡΙΛΗΨΗ

Μελετήθηκε η συμπεριφορά των εντόμων που επισκέπτονται τα άνθη του μάραθου (*Foeniculum vulgare* Mill.) σε σχέση με πέντε περιβαλλοντικές μεταβλητές. Παρατηρήσεις σε διάφορα είδη εντόμων έγιναν κατά το διάστημα Φεβρουαρίου-Μαρτίου σε εβδομαδιαία διαστήματα καθ' όλη την περίοδο ανθοφορίας. Οι ωριαίες μετρήσεις σε μεμονωμένα έντομα-επισκέπτες πραγματοποιούνταν στην αρχή κάθε ώρας, από την έναρξη έως τη διακοπή των καθημερινών δραστηριοτήτων. Μεταξύ 21 ειδών εντόμων, το *Apis florea* ήταν το πιο άφθονο, αντιπροσωπεύοντας περισσότερο από το 92,69% των συνολικών επισκεπτών. Η πτητική δραστηριότητα ξεκινούσε όταν οι περιβαλλοντικές μεταβλητές ξεπερνούσαν ένα ελάχιστο όριο, ενώ σταματούσε κυρίως λόγω μείωσης της έντασης του φωτός και της ακτινοβολίας. Ο πληθυσμός των εντόμων έδειξε σημαντική και θετική συσχέτιση με τη θερμοκρασία του αέρα, την ένταση φωτός, την ηλιακή ακτινοβολία και τη συγκέντρωση σακχάρου στο νέκταρ, και αρνητική συσχέτιση με τη σχετική υγρασία. Ωστόσο, η ανάλυση του συντελεστή διαδρομών αποκάλυψε ότι η άμεση επίδραση της ηλιακής ακτινοβολίας ήταν υψηλή και θετική, ακολουθούμενη από τη θερμοκρασία του αέρα και την ένταση του φωτός, ενώ η άμεση επίδραση της σχετικής υγρασίας ήταν χαμηλή και αρνητική. Η άμεση επίδραση της συγκέντρωσης σακχάρου στο νέκταρ ήταν θετική αλλά αμελητέα. Η ανάλυση του συντελεστή διαδρομών παρείχε σαφέστερη κατανόηση των επιπτώσεων σε σύγκριση με την απλή ανάλυση συσχέτισης. Κατά μέσο όρο, το *A. florea* επισκέφτηκε 7,31 ± 0,73 ταξιανθίες και 19,13 ± 0,39 ανθίδια ανά λεπτό σε διάφορες ώρες της ημέρας. Τα αγροτεμάχια που επικονιάστηκαν από έντομα παρήγαγαν σημαντικά περισσότερους σπόρους με μεγαλύτερο βάρος σε σύγκριση με αυτά που απομονώθηκαν από τις επισκέψεις εντόμων. Τα άνθη του μάραθου εμφάνισαν ένα διτροπικό μοντέλο νεκταροέκκρισης. Προφανώς, η επικονίαση των εντόμων πρέπει να ενθαρρύνεται με στόχο τη βελτίωση της ποιότητας και της ποσότητας των παραγόμενων σπόρων.

