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Bioecology and Domiciliation of the Alkali Bee, *Hoplonomia westwoodi* (Gribodo, 1894) (Hymenoptera: Halictidae: Nomiinae) from India

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Abstract

The nesting biology of the alkali bee, *Hoplonomia westwoodi*, a ground-nesting solitary bee in India is described. The typical soil-nest consisted of the main tunnel terminating in a series of circular cells. The number of cells per nest varied from 2 to 4 (n = 6; $\bar{x}$ = 2.67). Polypropylene bag and pot culture studies revealed that the bees most preferred red soil + FYM (1:1) for nesting. Maximum foraging activity was recorded between 8:00 and 13:00 hours. Though *H. westwoodi* bees were active throughout the year, higher foraging activity was found from March to June. This species being polyectic, foraged on flowering plants of families *viz.*, Myrtaceae, Lamiaceae, Portulacaceae, Convolvulaceae, Lythraceae, Meliaceae, Rubiaceae, Solanaceae, Cucurbitaceae, Asteraceae, Fabaceae, and Malvaceae. A cleptoparasite, *Eupetersia* sp. (Hymenoptera: Halictidae) is recorded for the first time, parasitizing on *Hoplonomia* species.

Introduction

Crop plants are effectively pollinated by one or more non-*Apis* bees (Parker et al., 1987; Klein et al., 2007), including several ground-nesting species (Cane, 1997). The most familiar bee families are Halictidae (sweat bees), Megachilidae (leaf-cutting bees and mason bees), and Apidae (carpenter bees, bumblebees, and honey bees). A few of the non-*Apis* solitary bees effectively managed for pollination are *Megachile rotundata* F. (alfalfa and canola), *Nomia melanderi* Latreille (alfalfa) and *Osmia lignaria* Say (almond, apple, cherries) in the USA, where they nest in the crop fields or greenhouses (Cane, 2008; Peterson & Artz, 2014). These bees are highly efficient pollinators, providing much-needed diversity in agricultural ecosystems (Peterson & Artz, 2014). Halictid bees play a vital role in the pollination ecology of a region (Karunaratne et al., 2005). The alkali bee, *Nomia* spp. (Hymenoptera: Halictidae) are highly efficient and effective pollinators and are used in large-scale pollination of leguminous crops (Cane, 2002). The world's only intensively managed ground-nesting bee, the alkali bee (*Nomia melanderi* Cockerell), has been used for over 50 years in alfalfa (*Medicago sativa* L.) seed production (Cane, 2008). Apart from a study by Yankit et al. (2018) on using a species of *Bombus* to pollinate tomatoes, there have been hardly any studies conducted in India on managing and utilizing non-*Apis* bees for crop pollination.

The subfamily Nomiinae (Halictidae: Hymenoptera) comprises 600 species with worldwide distribution, except in South America (Astafurova & Pesenko, 2005) and the Oriental fauna includes 154 valid species (Pannure & Belavadi, 2017). This subfamily is represented by 15 genera and 72 species from India (Saini & Rathor, 2012), of which 48 species are under 13 genera occurring in south India (Pannure & Belavadi, 2017). The genus *Hoplonomia* Ashmead, mostly Oriental in distribution (Ascher & Pickering, 2021), is represented by at least five species in India. *Hoplonomia westwoodi* (Gribodo, 1894) is a common species of southern India, recorded as an important pollinator of many cultivated crops (Udayakumar and Shivalingaswamy, 2018). To utilize this species for enhancing pollination in cultivated crops, it is essential to understand its nesting behavior, foraging preferences, and artificial nesting sites. The present study aims to study the seasonal activity, foraging, and nesting behavior of *H. westwoodi* and to standardize its artificial domiciliation.

Material and methods

Study site

The present study was conducted at the GKVK Campus of the University of Agricultural Sciences, Bangalore, India (12.97° N and 77.59° E; 924 m.a.s.l.) from 2019-20. The study site recorded a mean maximum temperature of 29.5 °C, mean minimum temperature of 18.2 °C, mean annual precipitation of 915.8 mm, mean relative humidity of 68.5%, and wind velocity of 6.40 km/h (https://www.uasbangalore.edu.in/index.php/research-en/agrometerology-en). The area of the experimental site measured 0.5 acres encompassing rich and diverse bee flora throughout the year.

Seasonal activity and foraging behavior

The seasonal incidence of *H. westwoodi* was studied at three locations (Bee park, Medicinal plants garden, Horticulture garden) in UAS, GKVK Bangalore, and at one location (College of Sericulture, Chintamani) in Chikkaballapur (13.33° N and 78.09° E) from November 2019 to November 2020. The sweep net method was used at weekly intervals to sample bees foraging over the flora. Bees were collected between 08:00 hr to 14:00 hr during the days of observation. The collected bees were killed using ethyl acetate and were brought to the laboratory for further processing and identification.

The foraging activity was recorded by observing the number of bees entering and exiting the nest. The number of pollen collection trips made by the adult female was observed between 6:00 to 17:30 hr for three days per week. The bee foraging pattern and peak foraging period were recorded. Observations on the natural enemies of alkali bees in the artificial nesting structures were also recorded during the study period.

Floral preference of H. westwoodi

Flowering plants in the experimental farm were observed for visitation by the bees during the entire study period. The different families of flowering plants preferred by the bees for foraging were observed at fortnightly intervals and recorded. The number of visits made by *H. westwoodi* per five minutes time period per flower was recorded at different time intervals, 8:00-9:00 hr, 10:00-11:00 hr, 12:00-13:00 hr, 14:00-15:00 hr, and 16:00 to 17:00 hr.

Artificial nesting structures

Polypropylene bag and pot culture experiments were conducted to determine the soil preference of bees for nesting. Different soil types, sand and FYM ratio were selected, *viz*., Red soil, Red soil + Sand (1:1), Red soil + Sand (3:1), Red Soil + Sand (9:1), Red soil +Sand +FYM (2:1:1), Red soil + Sand + FYM (7.5:1.5:1), Red soil + FYM (1:1) and FYM. The chosen substrates were filled in polypropylene bags of sizes 25x40 cm, 15x30 cm, 15x10 cm, and in plastic pots of 15x17 cm at 3 replications. The nesting structures were kept in the shade at Bee Park, UAS, GKVK, Bangalore, and close to flowering plants to attract foraging alkali bees for nesting. Weekly observations of nest-building activity in artificial nesting structures from November 2019 to November 2020 were recorded. The mean number of nests constructed on each substrate was recorded to determine soil substrate, best accepted by alkali bees. The presence of a new turret coupled with bee activity was used as an indication of a newly formed nest.

Nesting substrate characterization

Five hundred grams of soil was collected from all the treatments to analyze pH, electric conductivity, organic carbon, sand, silt, clay, and texture as per standard protocols (Jackson, 1973; Piper, 1966; Walkley & Black, 1934).

Nest dissection studies

Nest dissection was made to study the nest characteristics. The nesting medium was made slightly wet with water. After 10 min, the structures were kept on a wooden plank on the floor, as soon as water percolated into the soil. The pot was cut into two halves with a hot knife and the nest was exposed. The polypropylene bags were torn to open up the nests. The soil was removed gradually, starting from the periphery to expose the nest components. Tunnel length and width, number of cells built, number of cells with active brood, number of empty cells, and number of adult bees were recorded. The distance between nests, nest size, length of the turret, the diameter of the entrance, burrow diameters, nest depth, and other parameters were also recorded. The brood clusters were cut open to examine the inner contents. By injecting a thin slurry of plaster-of-paris and water into the nest, its architecture was molded and allowed to harden. The nest molds were then excavated using a small knife and shovel and preserved for further studies.

Ten nest entrances were closed at dusk and brought to the laboratory for further analysis. The nest's height from the soil surface was measured using a measuring tape. The nests were refrigerated for 8 to 10 hr to kill the inhabitants. Once nests were fully exposed, all contents like the presence of pollen-masses, and immature stages were recorded, and photos were clicked with a Sony DSC 160 digital camera.

Voucher specimens of *H. westwoodi* were deposited in the collections of the Department of Agricultural Entomology, University of Agricultural Sciences, Bangalore.

Statistical Analysis:

The data was analyzed by using statistical software SPSS.20 version. The study variable follows Poisson distribution; hence to achieve normal distribution, the square root transformation was used. Two-factor analysis of variance was used to know the interaction effect of soil substrate and nest structure. The Regression method was used to analyze the relationship between soil characters and nest occupancy by bees.

Results

Preference for nesting substrate

The number of nests recorded with different nesting structures and substrates showed statistically significant differences (Table 1). The effects of different soil nesting substrates *viz*., soil, sand, and FYM materials (factor B) used for the formation of nests are also statistically significant (*F stat = 30.06 and P = 0.0001*, *α = 1%*). The results indicated that there was a significant influence of soil types, sand, and FYM on the formation of nests by the bees. The nesting substrates used for nest construction showed statistically significant differences among the treatments in 25x40 polypropylene bags. The number of nests ranged between 1.00 and 12.67. Red soil + FYM (1:1) was the most preferred substrate (12.67), followed by Red soil + Sand + FYM (2:1:1). Bees could not construct a nest with FYM alone. The minimum number of nests (1) was recorded in Red soil +Sand (1:1). The most preferred nesting structure was 25x40 cm polypropylene bags with the soil substrate Red soil + FYM (1:1) followed by Red soil + Sand + FYM (2:1:1). The effect of different types of nesting structures (factor A) used for nest construction was statistically significant (*F stat = 203.74 and P = 0.0001*, *α = 1%*). It indicated that the bees used definite material for nest construction. This is also clear from F- statistics (203.74) and the corresponding probability value. The average number of nests occupied in 25x40 cm polypropylene bags was significantly higher compared to the 15x30 cm polypropylene bags, 15x10 cm polypropylene bags, and 15x17 cm plastic pots. The interaction of these two factors, that is the combined effect of various levels of nesting structure (factor A) and nesting substrate used (factor B) was also significant (*F stat = 19.38 and P = 0.0001*, *α = 1%*). It means there is an impact of both factors on nest construction. The coefficient of variation (4.09%) was optimum for both factors in the field condition as it showed < 20% of variation. The active nesting period recorded was from February to July, and the nesting activity was reduced after the initiation of the monsoon rains.

Nesting behavior and Nest structure

The female bees were found digging nest burrows with the provided nesting medium throughout the day. Bees constructed nests by digging the soil with mandibles and putting the mud outside using their legs (Fig 3g).

The nest's entrance began with a turret ranging from 0.6 to 1 cm (n=7) in height with a diameter of 0.7 to 1.2 cm (n=11). A nest opening was present at the apex of the turret (Fig 3e).

Table 1. Preference of nesting substrate and nesting structure by *H. westwoodi*.

Soil nesting materials (B)	Average number of nests in different types of nesting structure (A) (Height x Diameter) in cm				
	Polypropylene bag (25x40)	**Polypropylene bag (15x30)**	**Polypropylene bag (15x10)**	**Plastic Pot (15x17)**	**Mean B**
Red soil	1.67 (1.27)	0.00 (0.50)	0.00(0.50)	0.00(0.50)	0.42 (0.69)
Red soil + Sand (1:1)	1.00 (0.97)	0.00(0.50)	0.33 (0.67)	0.00(0.50)	0.33(0.66)
Red soil + Sand (3:1)	2.67 (1.62)	0.00(0.50)	0.00(0.50)	0.00(0.50)	0.67(0.78)
Red Soil + Sand (9:1)	1.00 (1.00)	0.00(0.50)	0.00(0.50)	0.33(0.67)	0.33(0.67)
Red soil +Sand +FYM (2:1:1)	6.33 (2.51)	0.33(0.67)	0.00(0.50)	0.00(0.50)	1.67(1.05)
Red soil + Sand +FYM (7.5:1.5:1)	2.67 (1.62)	0.67 (0.83)	0.00(0.50)	0.00(0.50)	0.83(0.86)
Red soil +FYM (1:1)	12.67(3.55)	0.67(0.83)	0.33(0.67)	0.33(0.67)	3.50(1.43)
FYM	0.00 (0.50)	0.00(0.50)	0.00(0.50)	0.00(0.50)	0.00(0.50)
Mean A	**3.50 (1.63)**	**0.21(0.60)**	**0.08 (0.54)**	**0.08 (0.54)**	**0.97(0.83)**
Sources	**F-Value**	**CD**	**CV (%)**		
Factor A (Nesting structure)	203.74**	0.11			
Factor B (Nesting material)	30.07**	0.15	4.09%		
Interaction A X B	19.38**	0.3			

The value in the parenthesis is the square-root transformed data
Note: ** Significant at 1% level of significance.

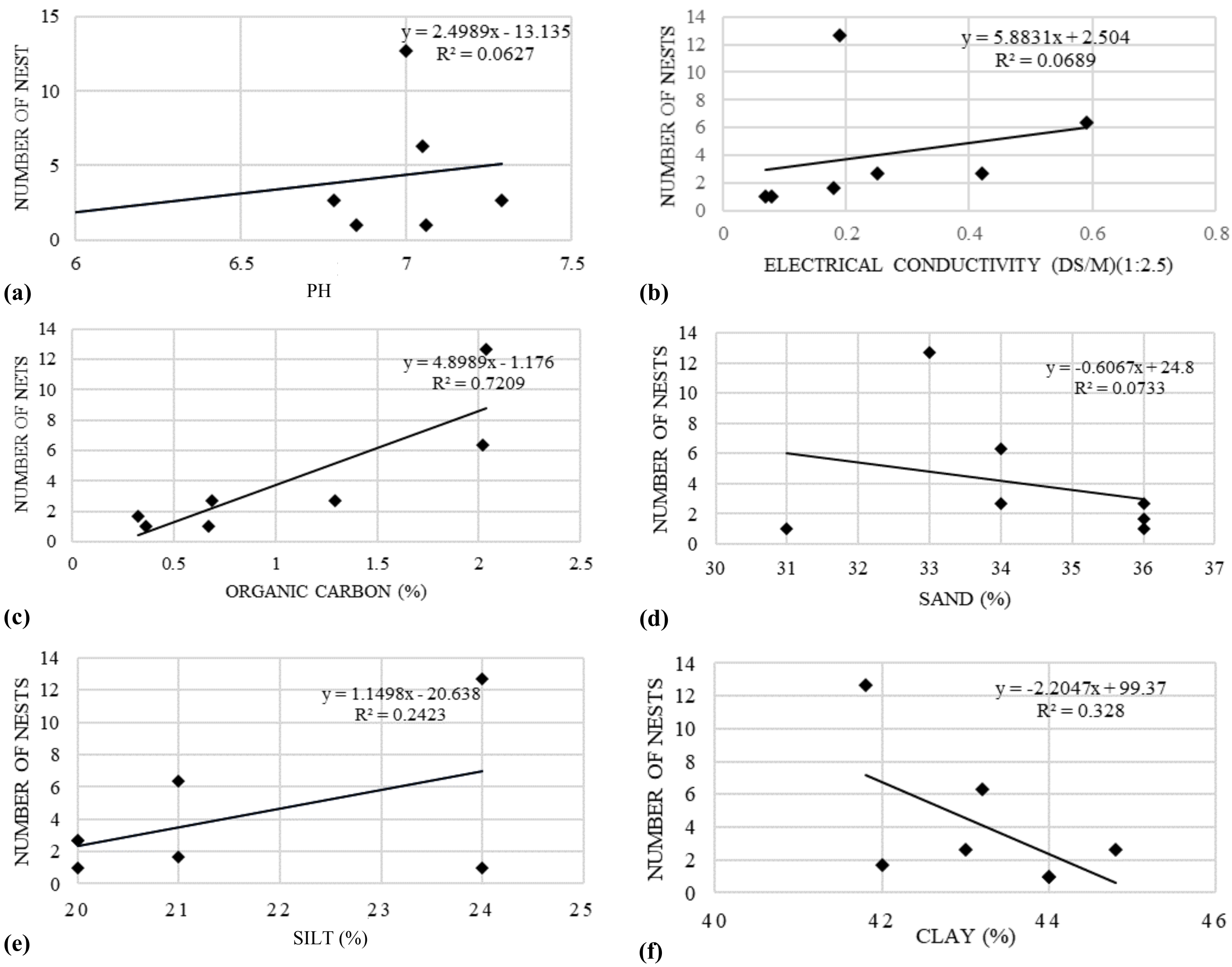


Fig 1. Relationship between soil characteristics and nest occupancy by H. *westwoodi.*

The internal surface of the turret was smooth. The external surface, however, was rough. The nests were branched and interconnected with more than one nest entrance. The total length of the untwined nest ranged from 18 to 28 cm (n=6). The nest burrows were as close as 2 to 12 cm (n=11). Each nest had an entrance hole leading into a shaft of varying depth (12-14.5 cm, n=6). A cluster of earthen brood cells was found at the end of the shaft. Bees constructed brood cells in pots from a depth of 12 cm. The numbers of brood cells in the isolated nest (n=6) ranged from two to four. Brood cells were cylindrical to oval in shape, with the walls coated with waterproof secretion (Fig 3f). The inner brood cell linings were pliable, smooth, thin, waxy, and translucent, preventing water entry. The height and diameter of brood cells ranged from 1.2 to 2.5cm (n=16) and 0.5 to 1cm (n=16), respectively. The adult bee laid translucent eggs on the pollen mass (Fig 4). The weight of the pollen mass was 0.067g (n=1). Larval feces were deposited at the bottom of the cell. The cast skin was found inside the brood cell. The cells contained different life stages, *viz*., eggs, pre-defecating and post defecating larvae, pupae, and adults.

Relationship between the number of nests and soil characteristics

Soil characteristics varied among different treatments evaluated for nest occupancy by *H. westwoodi* (Table 3). The typical nesting substrate of *H. westwoodi* consisted of clay loamy textured red soil. The pH of different treatments ranged from 5.97 to 7.29, weakly acidic to weakly alkaline. There was a weak positive correlation between the number of nests occupied by *H. westwoodi* and the pH of the soil substrate provided (r=0.25, Fig 1a). The maximum number of nests (n=12.67) was recorded in Red soil + FYM (1:1) with a pH of 7.04. The electrical conductivity of nest substrate with maximum nest occupancy was 0.19 ds/m (r=0.26, Fig 1b). The percent organic matter among the treatments ranged between 0.3 and 2.03. Consequently, there was a highly positive correlation between the number of nests occupied by *H. westwoodi* and the percent organic matter present in the soil (r=0.85, Fig 1c). The maximum number of nests occupied was found in treatment with organic matter (2.03%). The percent of sand in different treatments ranged from 31 to 36%.

Table 2. Nest infrastructure of *H. westwoodi*

Nest Parameters	Mean ± SD	Range
Diameter of entrance (cm)	0.88 ± 0.14 (n=11)	0.7-1.2
Closeness of nest burrow (cm)	5.83 ± 3.49 (n=11)	2 -12
Depth of the nest (cm)	13.58 ± 0.97 (n=6)	12-14.5
Shaft depth (cm)	4.17 ± 1.33 (n=6)	2.5-6.5
Total Length of the nest (cm)	23 ± 3.89 (n=6)	18-28
Height of the tumuli (cm)	0.9 ± 0.15 (n=7)	0.6-1
Number of brood cells	2.67 ± 1.03 (n=6)	2-4
Height of the brood cell (cm)	1.8 ± 0.44 (n=16)	1.2-2.5
Diameter of brood cell (cm)	0.8 ± 0.25 (n=16)	0.5-1
Weight of the bee bread (gm)	0.067 (n=1)	-
Weight of the just emerged bee (gm)	0.04 ± 0.002 (n=4)	0.037-0.044

In contrast, there was a weakly negative correlation between the number of nests occupied by *H. westwoodi* and percent sand (r=-0.27, Fig 1d). The silt percent in the different treatments ranged from 20 to 24%. There was a positive correlation between the number of nests occupied by *H. westwoodi* and the percent silt in the soil substrate provided (r=0.49, Fig 1e). The best-preferred portion was 24% silt by *H. westwoodi.* The clay percent in the different soil treatments ranged from 41.8 to 44.8%, although there was a negative correlation between the two (r=-0.57, Fig 1f).

Biology

The various life stages (Fig 4) of *H. westwoodi* are described below.

Egg: Eggs were present only in brood cells adequately provisioned with pollen store. The bee bread had a semisolid consistency, found at the bottom of the brood cell. The color of bee bread was creamy yellow and comprised two floral sources, *Azadirachta indica* and *Mellettia pinnata*. The average weight of bee bread was 0.067gm (n=1). The egg was creamy white, cylindrical, slightly arched, and singly laid on the brood food. The bent caudal ends of the egg were attached to brood food.

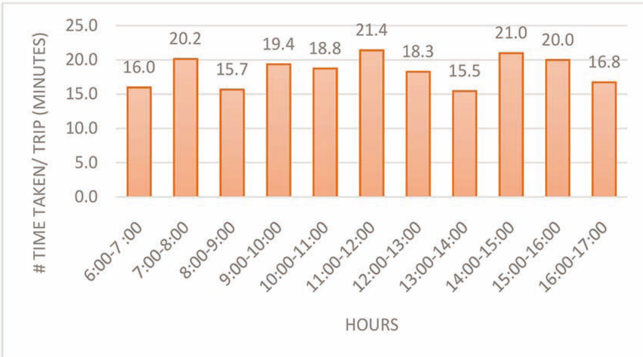
Larva: Newly hatched larva was straight and found on the top of the brood food. The body became 'C' shaped and robust as the larva grew. The second instar larva had slightly pigmented mandibles. The adult larva was swollen, and only a minor amount of unutilized brood food was left out in the brood cell. The last instar larva consumed the remaining provisions and also the cell linings. The head capsule was well developed with two well-developed mandibles. It was elongated without any legs on the thorax and abdomen.

Prepupa: The body of the fully-grown larva shrank to form the prepupa. The cell covering the prepupa neither had any brood food nor wax coatings. Prepupa is molted into an exarate pupa without any covering within the brood cell. The newly formed pupa was yellow with yellow compound eyes. As the pupa matured, the eye color changed from yellow to orange, brown, and finally black. Under *in-vitro* conditions, the fully-grown pupa transformed into an adult bee within a fortnight.

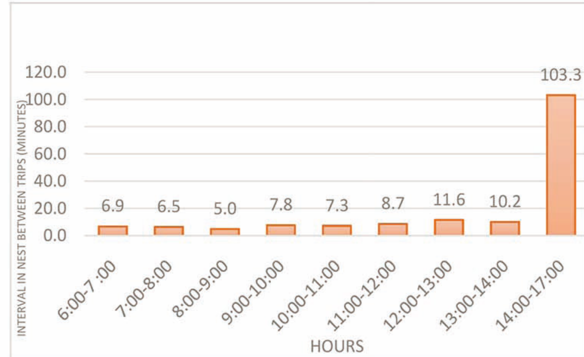
Adult: The newly emerged adult bee continued within the brood cell for two to three days. It cleaned compound eyes with its forelegs, rubbed its gaster with its hind legs, and flapped its wings. The weight of just emerged adult bee varied from 0.037 to 0.044g (n=4).

Table 3. Soil characteristics of substrate provided in artificial nests for *H. westwoodi*.

Parameters	pH (1:2.5)	Electrical conductivity (dS/m) (1:2.5)	Organic Carbon (%)	Sand (%)	Silt (%)	Clay (%)	Texture
Red soil	5.97	0.18	0.19	36	21	42	Clay Loam
Red soil + Sand (1:1)	7.06	0.07	0.21	31	24	44	Clay Loam
Red soil + Sand (3:1)	6.78	0.25	0.4	34	20	44.8	Clay Loam
Red Soil + Sand (9:1)	6.85	0.08	0.39	36	20	44	Clay Loam
Red soil +Sand +FYM (2:1:1)	7.05	0.59	1.17	34	21	43.2	Clay Loam
Red soil + Sand +FYM (7.5:1.5:1)	7.29	0.42	0.75	36	20	43	Clay Loam
Red soil +FYM (1:1)	7	0.19	1.11	33	24	41.8	Clay Loam
FYM	6.5	0.11	1.65	20	10	16	Loamy



(a)



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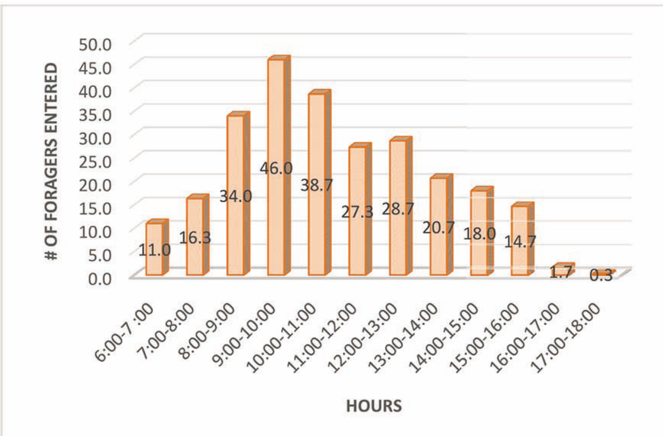

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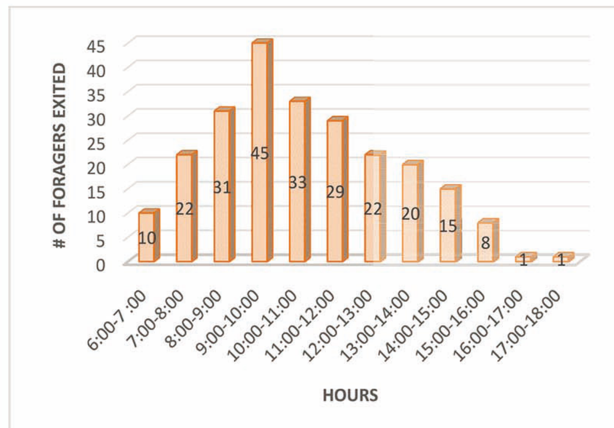

(b)

Fig 2. Daily cycle of foraging activity of H. *westwoodi* (a) Time taken per trip, (b) Time interval in the nest between trips, (c) Number of bees observed returning to the nest, d) Number of bees observed leaving the nest.

Foraging activity and floral preference

The number of bees exiting was most frequent in the morning hours and dwindled by the afternoon. The maximum foraging activity was recorded between 8:00-13:00 hrs, with a peak around 10 am (Fig 2c, 2d). The initiation of the foraging activity was at 6:00-6:30 hrs (n=25), and termination of the foraging activity was observed between 15:00-17:30 hrs (n=25). The foraging time per trip by a bee ranged from 2 to 60 min, with an average of 18.41 min (n=140). Intervals in the nest between trips ranged from 2 to 140 minutes with an average of 11.98 mins (n=140) (Table 4). However, the most frequently observed interval was approximately 5 to 10 min during active hours. But, there was no significant difference between the duration of trips across time (F=0.62, P=0.79, F_{crit} = 1.90, Fig 2a). Bees spent less time in the nest between successive trips during morning hours than in the afternoon (Fig 2b). The number of trips per bee per day ranged from 9 to 22, with an average of 15.25 (n=20).

A cleptoparasitic Halictid bee, *Eupetersia* sp. (Fig 3h), was often observed on or near nests. It was observed entering a nest on four occasions, where the parasitic bee stayed for over five to ten minutes, indicating possible parasitization.

H. westwoodi was collected from various crops in UAS, GKVK, Bengaluru on different kinds of crops, *viz*., Guava (*Psidium guajava* L.; Myrtaceae), Leucas (*Leucas aspera*; Willd.) Link. Lamiaceae), Holy basil (*Ocimum tenuiflorum* L.; Lamiaceae), Portulaca (*Portulaca oleracea* L.; Portulacaceae), Jacquemon (*Jacquemontia violacea;* Kunth. Convolvulaceae), Cuphea (*Cuphea hyssopifolia* Kunth; Lythraceae), Neem (*Azadirachta indica* A. Juss.; Meliaceae), Fire bush (*Hamelia patens* Jacq.; Rubiaceae), Brinjal (*Solanum melongena* L.; Solanaceae), Tomato (*Lycopersicon esculentum* L.; Solanaceae), Chilli (*Capsicum annum* L.; Solanaceae), Cucumber (*Cucumis sativus* L.; Cucurbitaceae), Ridge Gourd (*Luffa acutangula* L.; Cucurbitaceae), Sunflower (*Helianthus annuus* L.; Asteraceae), Red Gram (*Cajanus cajan* L.; Fabaceae), Pongamia (*Pongamia pinnata* L.; Fabaceae) and okra (*Abelmoschus esculentus* L.; Malvaceae). This wide range of flora visited by *H. westwoodi* indicated that it is polylectic.

Table 4. Foraging activity of *H. westwoodi*.

Foraging activity	Time taken/trip (n=140)	Interval in the nest between trips (n=140)	Average number of trips per day/forager (n=20)
Range	2-60 minutes	2-140 minutes	9-22
Mean ± SD	18.41 ±10.11minutes	11.98 ± 21.22 minutes	15.25

a. Nesting structure **b. Brood chamber** **c. Brood chamber**

d. Gaurding bees inside the artificial nesting site **e. Nest turrets** **f. Newly emerged bee**

g. Adult bee entering into nest **h. *Eupetersia* sp. parasitic on H. westwoodi**

Fig 3. Nest architecture of H. *westwoodi*.

Seasonal activity

The seasonal occurrence of *H. westwoodi* was observed at the Bee Park, Medicinal and aromatic plants garden in UAS, GKVK, campus, Bangalore, and at College of Sericulture, Chintamani campus Chikkaballapura during the study period.

Bee activity in Bangalore

Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
*	*	****	****	****	****	***	***	***	**	**	**

Bee activity in Chikkaballapura

Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
*	*	-	****	****	****	***	***	***	**	**	**

****	***	**	*	-
High	Moderate	Less	Very less	Nil

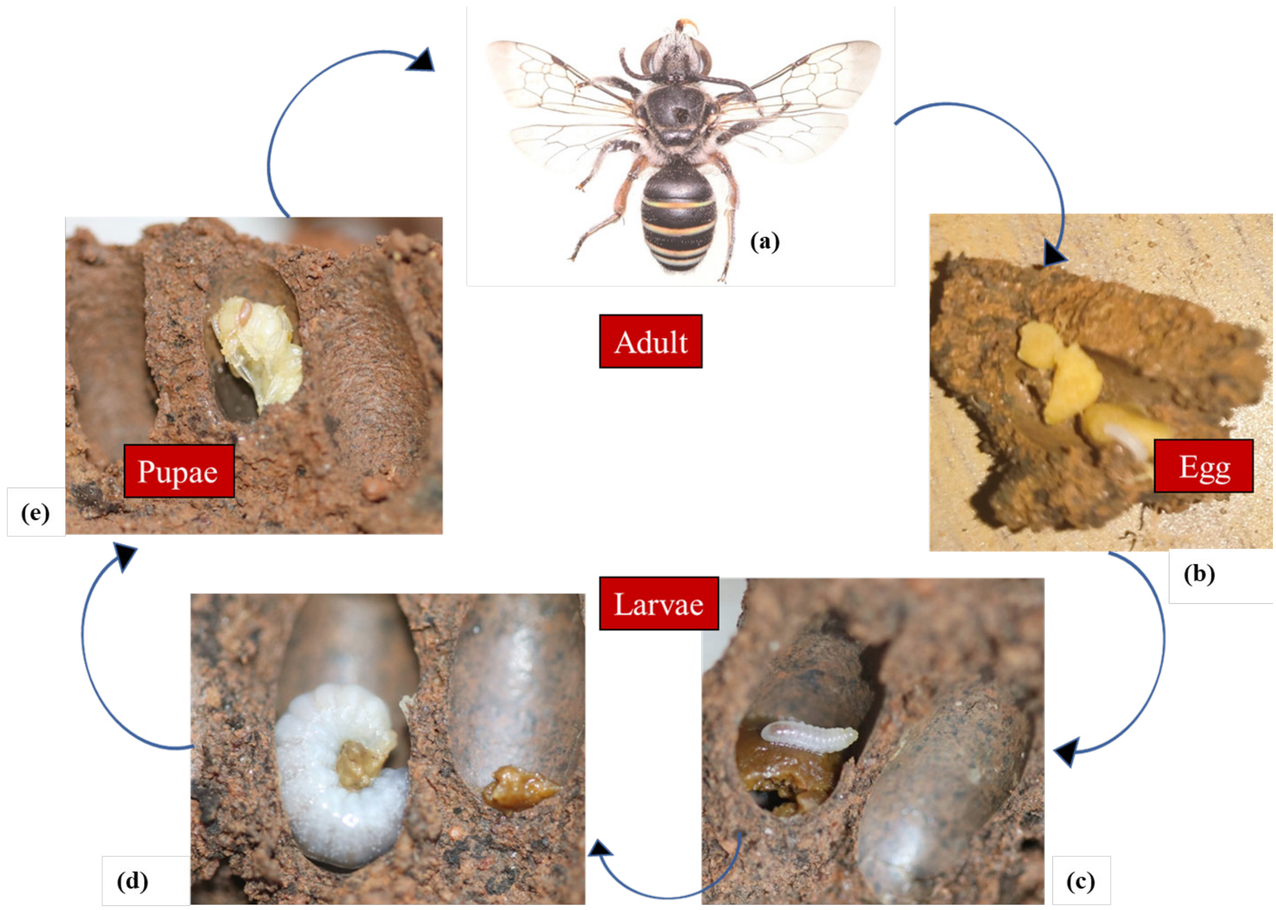

Fig 4. Life stages of H. *westwoodi*. (a). Adult male, (b). Egg with cell provisions, (c) & (d). Larvae at different stages (e). Pupae.

Discussion

Artificial nesting structures and their preference

The alkali bee, *H. westwoodi,* is a solitary ground-nesting bee distributed in India, Afghanistan, Pakistan, and Sri Lanka. As its name suggests, it can be found nesting in alkali soil (Batra, 1966). It chooses to nest in bare soil that remains moist but not too wet and too dry on top. The nests occur naturally in areas where a layer of hardpan exists in alkali soils. The study successfully provided an artificial nesting medium for *H. westwoodi*. Among the different types of nesting structures, the maximum nesting preference by *H. westwoodi* was in 25x40 polypropylene bags. Among the different substrates, the most preferred was Red soil + FYM (1:1) followed by Red soil +Sand +FYM (2:1:1). Similar observations on artificial nesting structures for *H. westwoodi* were recorded by Udayakumar and Shivalingaswamy (2018). They found active nesting structures for *H. westwoodi* to be polypropylene bags (30x30 cm) and earthen flower pots (60x30 cm) filled with soil. Shade, good drainage, and the absence of excess roots in pots and polypropylene bags were the major factors in deciding the choice of nesting sites. Sheltered places were always beneficial to maintain their nest cool. Many soil nesting bees also show similar preferences in nest-site selection (Sandeep & Muthuraman, 2019).

Though each bee digs its own nest, soils nesting solitary bees frequently construct their nest together, forming dense aggregations. The gregarious nesting behavior was reported in several species of ground-nesting bees (Michener et al., 1958). It is credited that female philopatry was the key factor for the aggregation of nests, as neighboring seemingly equivalent sites in the same embankments remained unused. The phenomenon of philopatry consists of female bees mainly fascinated by sites having holes or depressions where other females are already constructing nests. Thus, philopatry ends up in the formation of a nest congregation. In such a situation, there is overcrowding of nests and the nearest neighbor distance becomes very low. Typically, horizontal and vertical nests were constructed only in well-drained soils. A similar kind of behavior was observed in the current study. An average of 12 nests was observed in a polypropylene bag (25x40 cm), including horizontal and vertical entrances. Bees used drainage holes provided at the bottom of polypropylene bags for horizontal entrances or exits. The maximum number of nests was found closer to the peripheral edges of polypropylene bags rather than at the center. When the nest was built near the periphery of the pot, the sidewall of the polypropylene bags offered good support to the nest. Nest congregations in solitary bees ensured reproductive success and resulted in the natural enemy's dilution effect because of overcrowding of nests and reduction in the nearest neighbor distance (Sandeep & Muthuraman, 2019).

Relationship between the number of nests and soil characteristics

There are certain basic requirements of an acceptable bed for nesting by alkali bees. It essentially has a moisture source capable of rising to the surface. Nesting bees typically need a hardpan layer a foot or more below a porous soil that tends to hold the moisture and allow movement from the source of supply to the surface. Situations should permit quick drainage of surface water. The underlayer should range in texture from silt loam to sandy loam with not more than 7 percent clay-size particles. The current investigation found maximum nest occupancy when the clay percentage was lower in the soil with a clay loam mixture. Good soil texture boosts digging by bees. It allows a nonstop capillary flow of subsurface water towards the surface, replacing water in the upper layers at a rate equal to or slightly greater than the rate of evaporation (Cane, 1991). Unchanging soil moisture and good nest excavating conditions largely depend on the percentage composition of clay, sand, and silt, with clay preventing capillarity at levels greater than 25 percent. Soils high in the sand (45-80%) are difficult to seal, and excessive water movement and evaporation may occur. The present observations of least nest occupancy supported this condition when soil and sand in a 1:1 ratio were used. Soil categorized as silt loams with 2-6% fine silt and 42-68% coarse silt proved the best alkali bee beds. They contain 13-24% clay and 10-40% sand (Kaushik & Yadav, 2012). Soils of other halictids like *Lasioglossum* were analyzed by Cane (1991), which showed major levels of silt (*L. sisymbrii* Cockerell, *L. laevissimus* Smith: from 44% to 53.8%) and low percent of clay. In the present study, *H. westwoodi* was observed to prefer soils with low silt and high clay percent for nesting, possibly suggesting that the soil preference may slightly vary with the locations and species. Only some parts of a specific area may meet all the apparent conditions essential for nest initiation, and this may account for aggregation patterns at a landscape level (Polidori et al., 2010).

Nest infrastructure

Six artificial nest bags occupied with *H. westwoodi* were excavated in June 2020. The nest consisted of a vertical main burrow leading to a depth of 13.5 ±0.97 cm. A nest had interconnected horizontal and vertical burrows, which ended with a group of cells arranged horizontally. Similar nest architecture has been described in halictids like *Nomioides divisus* Cam., *Nomioides variegata* Blüthgen. (Batra, 1966) and in *N. melanderi* Latreille (Batra, 1970) in India. At the terminal part of the shaft, brood cells are constructed in clusters or a line in different soil nesting bees. The brood cells were in small clusters in the present study. The number of brood cells was 2 to 4, unlike in *Nomia melanderi* Latreille. which builds a great number of cells (5 to 24), depending upon the accessibility of food and the superiority of the substrate in which they are nesting (Abrol, 2012). Each cell was typically oval with the walls coated with a secretion. Cane and Carlson (1984) indicated that these linings could be secretions of Dufour's gland, consisting of triglycerides, and possibly function as a waterproofing layer.

As a solitary bee, *H. westwoodii*, a mass provisioner, seals off the cells after providing ~0.067 g of pollen and egg-laying. Similar observations have been made with other solitary bees by Yogeshkumar (2012).

Foraging activity

H. westwoodi was found broadly polylectic, actively foraging on a flora belonging to different plant families. The peak population is reached from June to November (Udayakumar & Shivalingaswamy, 2018). However, the peak nesting activity was recorded from February to July. After July there was a reduction in the nesting activity. Most likely this is due to the initiation of monsoon in the location which may lead to an increase in the soil moisture and low drainage, particularly in the polypropylene bags.

Natural enemies

A cleptoparasitic bee or wasp enters a nest of a solitary or social host, lays eggs in one or more brood cells, and then generally leaves the nest to search for further nests or to reappear later (Wcislo, 1987). In the present study, a species of *Eupetersia* was recorded as a cleptoparasite of *H. westwoodii*. This is the first record of parasitization of *H. westwoodii* by *Eupetersia* sp. Previously, there were reports of parasitization of *Eupetersia* sp. on *Lasioglossum* (Cameron, 1908) and some other halictids of the genus *Zonalictus* (Michener, 1978). At bee nesting sites, parasite females usually attempt to enter unguarded nests (Legewie, 1925; Knerer & Atwood, 1967; Knerer, 1973; Sick et al., 1991) to lay eggs in a newly provisioned brood cell. In solitary bee host species, nests continue unguarded while the host female bees are foraging. On the other hand, in primitively eusocial host species, such a situation occurs during the solitary stage of the nest cycle, but as soon as the first worker brood emerges, nest entrances are then usually congested by a guard bee (Knerer, 1969) refusing parasites and conspecific females from neighboring nests.

Conclusion

In the present investigation, an initial attempt at the development of an artificial nesting structure was carried out for *H. westwoodii*. The effects of different soil nesting substrates and nesting structures for the formation of nests by alkali bees were evaluated. Red soil + FYM (1:1) was the most preferred substrate and a higher number of nests were occupied in 25x40 cm polypropylene. Developed nesting structures will be used to increase the population of alkali bees and to achieve efficient pollination of various crops. The nest excavation, construction, and formation behavior of *H. westwoodi* are described. There was a positive correlation between the number of nests and the percent of organic matter present in the soil. The maximum number of nests occupied the soil with a pH of 7.04. The biology of *H. westwoodi* consisted of 4 stages and the weight of just emerged adult bee varied from 0.037- 0.044g (n=4) depending on the soil characteristics and weather conditions. The maximum foraging activity of bees was recorded between 8:00-13:00 hr with 9 to 22 forage trips per day. *H. westwoodi* is polylectic and visits a diverse flora. The peak of nesting activity was recorded from February to July in the study area. These findings on *H. westwoodii* will be very useful in framing the package for its utilization in pollinating crops.

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Authors' Contribution

KTV: conceptualization, supervision, and investigation.
NT: investigation, data curation, formal analysis, and writing
AP: bee specimens identification, investigation.
All authors have read and approved the manuscript.

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