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Integrating Natural Nest Characteristics into the Design of Sustainable Hives and Trap Nests for *Tetragonula iridipennis* (Smith) in the Western Ghats, India

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Abstract

The stingless bee species *Tetragonula iridipennis* (Hymenoptera: Apidae: Meliponinae) is native to India's Western Ghats, a biodiversity hotspot. It plays a critical role in pollination and ecosystem stability. This study aimed to develop suitable trap nests and hive designs for the sustainable maintenance of *T. iridipennis* by analyzing its natural nesting ecology and nest architecture. Seven trap nest designs and four hive types were evaluated based on parameters including brood size, the number of honey and pollen pots, honey pot segregation, brood temperature, and percentage increase in brood volume and storage pots. Among trap nests, reused *Apis cerana* hives performed best, followed by bamboo slits, wooden hives, and coconut shells. Hive design significantly influenced colony development. The rectangular box with two halves showed the highest brood volume and the greatest number of honey and pollen pots, while the rectangular box with two compartments had the lowest. However, honey pot segregation – important for hygienic honey harvesting – was observed only in the Utrecht University Tobago (UTOB) hive, which had two compartments. The best-performing design for colony growth lacked segregation. Brood temperature did not vary significantly across designs. These findings suggest the rectangular box with two halves is optimal for brood and resource production, but may not support clean honey harvesting. Future designs should combine the advantages of colony development and honey pot segregation. Such tailored hive models could support the conservation and sustainable beekeeping of *T. iridipennis* in the Western Ghats.

Introduction

The stingless bee species *Tetragonula iridipennis*, belonging to the family Apidae and subfamily Meliponinae, is native to the Western Ghats – a globally recognized biodiversity hotspot in India. This species plays a vital role in pollination and the maintenance of ecological balance and biodiversity (Heard, 1999). Named for its vestigial sting, *T. iridipennis* has attracted growing interest due to its ecological and economic importance (Fletcher et al., 2020). It is distinguished by its efficient pollination behavior, complex social structure, and production of valuable hive products

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such as honey, cerumen, and propolis (Suresh et al., 2012; Mayes et al., 2019; Charanakumar et al., 2022; Noorahya & Withaningsih, 2023). Its effectiveness as a pollinator is primarily attributed to its diverse foraging habits and its ability to visit a wide range of flowering plant species both in agricultural and forest habitats (Cortopassi-Laurino et al., 2006; Brown et al., 2016). However, the sustainable maintenance and conservation of *T. iridipennis* colonies and other native bees in the Indian subcontinent is increasingly threatened by habitat degradation, climate change, and a lack of appropriately designed hive structures (Warrit et al., 2023).

Unlike other bee species, stingless bees exhibit unique biology and nesting behavior. They construct hives in enclosed cavities where pollen, honey, and brood are intermixed (Bhatta et al., 2019; Noorahya & Withaningsih, 2023). Storage pots – typically elliptical and built using cerumen, a blend of beeswax and plant resins – are notably larger than brood cells. While honey and pollen pots are often intermixed, honey is sometimes arranged peripherally, with pollen pots located closer to the brood chamber.

Stingless bee colonies are exceptionally resilient. They are known for their resistance to pests and diseases, minimal dependence on artificial feeding, and ability to thrive with limited forage resources. Importantly, colonies have not shown absconding behavior over long periods. As highly social insects, *T. iridipennis* forms permanent colonies in natural cavities such as crevices, hollow logs, and old walls (Pavithra et al., 2012; Rasmussen, 2013; Bhatta et al., 2019). Additionally, their harmless nature makes them highly suitable for human interaction, especially in community-based apiculture initiatives.

In India, stingless bees are largely managed through traditional methods. Notably, the Kani tribes of the Kariyar region in the Western Ghats have developed indigenous techniques to rear these bees using split bamboo poles (Suresh et al., 2012). Internationally, a specialized hive for stingless bees – known as the Utrecht University Tobago Hive (UTOB hive) – has been developed in Tobago for controlled meliponiculture (Sommeijer, 1999). The practice of stingless beekeeping is gaining momentum due to the high medicinal value of their honey, which is known for its antioxidant, antimicrobial, and wound-healing properties (Scepankova, 2021). This honey is traditionally used to treat a range of ailments, including gastrointestinal disorders, ulcers, coughs, and ocular infections (Wille, 1983; Bhatta et al., 2020; Fletcher et al., 2020).

Despite these benefits, stingless bees remain underrepresented in formal apiculture research and development programs. The specialized nesting behavior, architectural preferences, space requirements, and ventilation needs of stingless bees differ significantly from those of *Apis mellifera* and *Apis cerana*, rendering conventional hive designs inadequate (Roubik, 2006). Poorly designed hives can hinder brood development, reduce honey yields, and increase the vulnerability of bees to pests and diseases (Camargo & Pedro, 2013). Moreover, the destructive honey extraction practices and challenges in separating honey from pollen – due to the bees' combined storage of these resources – further limit sustainable production. To date, most hive design studies have focused on *A. mellifera* and *A. cerana*, with limited attention to *T. iridipennis* in the Western Ghats (Heard, 1999).

Given these challenges, there is an urgent need to deepen our understanding of the nesting ecology of *T. iridipennis* and to develop context-specific trap nests and hive designs that meet the biological and ecological needs of this species. Such innovations will not only enhance colony health and productivity but also support conservation and sustainable meliponiculture practices in one of India's most ecologically sensitive regions.

Methodology

Study Area

This research was conducted from 2015 to 2022 in and around the apiary at the College of Forestry, Ponnampet, located in Kodagu district, Karnataka, India (12° N, 75°56' E; 867 m above mean sea level) (Figure 1). The study area experiences a tropical climate, with average annual temperatures ranging from 20 °C to 31 °C and annual rainfall between 2,000 mm and 4,000 mm (Devakumar et al., 2018; Gunaga et al., 2024). The region's diverse climatic and soil conditions, coupled with varied vegetation, provide a wide range of habitats suitable for different plant and animal species, thereby contributing to its rich biological diversity (Myers et al., 2000; Devakumar et al., 2018; Gunaga et al., 2024).

Analysis of Natural Nest Characteristics

A circular area with a 1.5 km radius from the established apiary (*Apis* species) was surveyed to locate stingless bee colonies and analyze their natural nest characteristics (Table 1). The selected locations were forage resource-rich areas surrounding the apiary, where the presence of stingless bee colonies was expected. Natural nest characteristics were studied by opening colonies found in various substrates, including wall cavities, wooden logs, termite mounds, and other sites such as empty *Apis cerana* hives, cement pipes, electric boards, and mud pots. A total of 13 colonies were examined. Before transferring the colonies to hive boxes, the following observations were recorded: presence or absence of an entrance tube, entrance length and width (cm), entrance height from the ground (cm), cavity dimensions (length, breadth, and height in cm), brood size (length, breadth, and height in cm), and the size of honey and pollen pots (mm) (Figure 2).

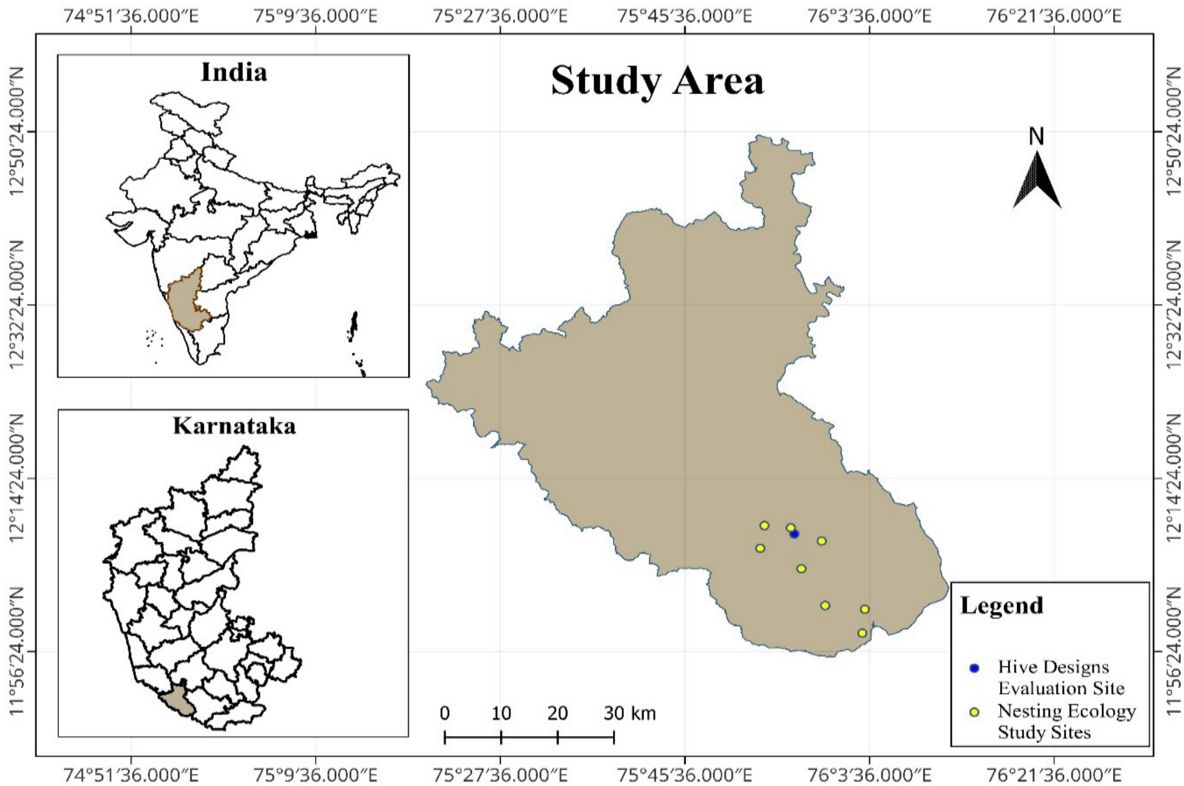

Fig 1. The study area is represented by a blue dot, which indicates the evaluation site for the hive designs, and yellow dots represent the nesting ecology study sites.

Development of Trap Nests

The trap nest experiment was conducted in farmers' fields within a 1.5 km radius of an established *Apis* species apiary to investigate efficient trap nest designs for the sustainable maintenance of *T. iridipennis*. In addition to old *Apis cerana* hives, six distinct types of trap nests were tested, all constructed from low-cost materials such as cement pipes, plastic bottles, bamboo slits, clay pots, wooden boxes, and coconut shells (Figure 3). Each trap nest type was evaluated using three different treatments, with three replications per treatment.

In the first treatment, stingless bee honey was used as an attractant; in the second, propolis was applied; and in the third (control), no attractant was used. The entrances of the first and second treatments for all seven trap nest types were also smeared with propolis to mimic natural stingless bee nest entrances. To block light exposure, transparent plastic bottles were wrapped in black polyethylene sheets. The traps were installed at two locations with a high density of natural stingless bee colonies. Observations were recorded from September 15, 2021, to March 15, 2022, to monitor colony swarming into the traps. Comprehensive findings were documented and supported with photographic evidence.

Table 1. Natural nest entrance and cavity characteristics of the bee colony found in different nesting substrates.

Colony	Protruding Entrance tube	Entrance height from ground (cm)	Entrance size (mm)		Cavity size (cm)		
			Length	Breadth	Length	Breadth	Height
Wall cavity	Not found	82.33 ± 3.06^{ab}	6.00 ± 1.00^{b}	4.00 ± 1.00^{b}	27.33 ± 1.53^{b}	27.33 ± 3.79^{ab}	17.00 ± 4.00^{b}
Wooden log	Found	39.33 ± 18.88^{b}	9.67 ± 4.93^{ab}	4.33 ± 1.53^{b}	38.00 ± 9.17^{a}	26.67 ± 10.97^{ab}	17.67 ± 9.29^{b}
Termite mound	Not found	109.33 ± 68.60^{ab}	6.67 ± 2.08^{b}	4.33 ± 0.58^{b}	22.67 ± 4.73^{bc}	28.00 ± 2.00^{ab}	18.00 ± 5.00^{b}
Cerena Hive	Not found	124.33 ± 44.00^{ab}	12.33 ± 4.73^{a}	6.67 ± 0.58^{a}	30.67 ± 5.86^{ab}	26.33 ± 1.53^{abc}	7.60 ± 0.36^{c}
Cement Pipe	Not found	89.00 ± 13.08^{ab}	11.33 ± 0.58^{ab}	3.13 ± 0.23^{b}	22.33 ± 2.08^{bc}	17.83 ± 5.58^{bc}	12.77 ± 2.25^{bc}
Electricboard	Found	163.33 ± 67.88^{a}	7.33 ± 1.53^{ab}	3.67 ± 0.58^{b}	16.67 ± 5.03^{c}	15.00 ± 9.64^{c}	7.00 ± 1.73^{c}
Mud pot	Not found	119.67 ± 74.85^{ab}	6.67 ± 1.15^{b}	4.50 ± 0.50^{b}	24.33 ± 2.52^{bc}	33.67 ± 1.53^{a}	26.83 ± 0.76^{a}
Mean		**103.90 ± 55.69**	**8.57 ± 3.37**	**4.38 ± 1.26**	**26.00 ± 7.76**	**24.98 ± 7.97**	**15.27 ± 7.49**
F value		**1.83**	**2.40**	**5.63**	**5.51**	**3.21**	**7.29**
Sig. ($p \leq 0.05$)		**NS**	**NS**	**0.00**	**0.00**	**0.03**	**0.00**

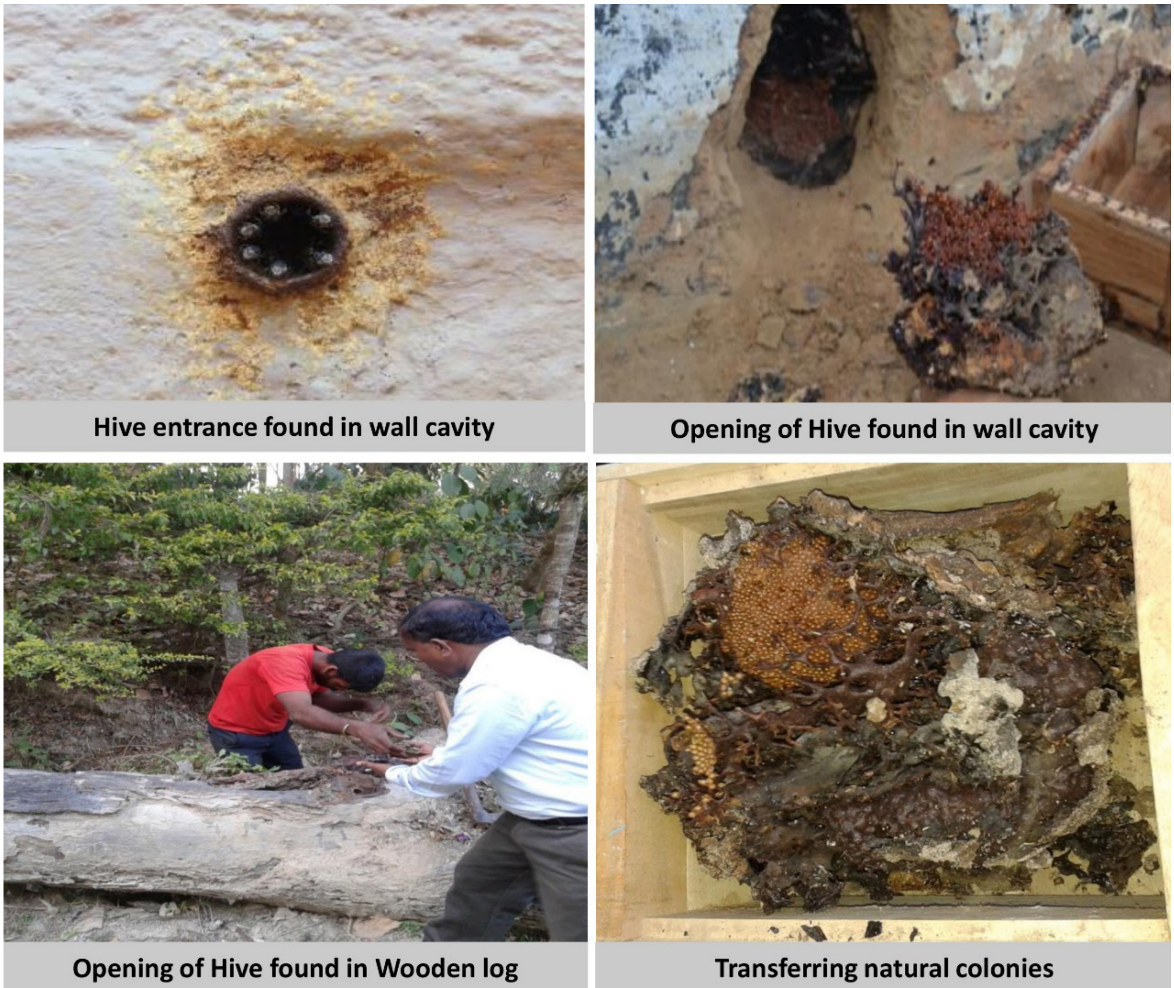

Fig 2. Measuring nesting characteristics and dissecting the *T. iridipennis* nest found in the house wall and wooden log before transferring them to the modern hive.

Fig 3. Setting up trap nests made up of bamboo slits, coconut shells, cement pipes, earthen pots, wooden hives, and plastic bottles to test their efficacy for capturing natural *T. iridipennis* colonies.

Hive Designs

Four stingless beehive designs were tested: the Utrecht University Tobago Hive (UTOB Hive), a modified UTOB Hive with two-story space, a rectangular box with two compartments, and a rectangular box with two halves (Figure 4).

UTOB Hive

The UTOB hive consisted of two chambers: a brood chamber (13 × 13 × 13 cm³ LBH) and a honey chamber (40 × 13 × 7 cm³ LBH). These two chambers were mounted on a wooden platform to form a single unit. A 2.5 cm-wide passage connected the honey and brood chambers, and an entrance hole was made in the honey chamber to serve as the main entry point for the colony (Figure 4).

UTOB Hive Modified to Provide Two-Story Space

This design also consisted of two chambers, each with the same dimensions as the UTOB brood chamber (13 × 13 × 13 cm³ LBH). The chambers were stacked vertically with a 2.5 cm diameter internal connecting hole. The lower chamber functioned as the brood chamber and included an entrance hole (Figure 4).

Rectangular Box with Two Compartments

A rectangular box was modified by joining two boxes of equal size (15 × 8 × 13 cm³ LBH) to create two compartments. A connecting hole was provided between the compartments, and an entrance hole was added. The compartment with the external opening served as the brood chamber (Figure 4).

Rectangular Box with Two Halves

This hive design included two halves, each measuring 25 × 10 × 6 cm³ LBH. The halves were joined at their open ends and stacked vertically to form a rectangular box. A connecting hole and an entrance hole were provided in one of the boxes. The internal space of one rectangular half measured 22 × 7.5 × 5 cm³ LBH.

All hives were constructed using teak wood (*Tectona grandis*) with a wall thickness of 2.5 cm. They were placed on stands 100 cm above the ground. Colonies of *T. iridipennis* with relatively uniform strength were transferred into the hives in September 2015-16.

Observations recorded included brood size (length, breadth, and height in cm), number of honey and pollen pots, and the presence or absence of honey pot segregation.

Fig 4. Four types of stingless beehive designs used in this study: 1. Utrecht University Tobago Hive (UTOB Hive), 2. UTOB Hive Modified to Provide Two-Story Space, 3. Rectangular Box with Two Compartments, and 4. Rectangular Box with Two Halves showing the arrangements of brood cells, honey pots, and pollen pots inside the hive.

The brood nest temperature was measured using a digital thermometer (Equinox®). The probe tip was placed on the surface of the brood nest, and the temperature was recorded (Figure 6). Observations were conducted from September to February, with five days of data collection per month. Temperature readings were taken three times each day: morning (9:00 am), afternoon (2:00 pm), and evening (6:00 pm). The average brood temperature for each hive was calculated by taking the mean of the three daily readings, followed by the average of the five-day means for each month.

Statistical Analysis

The experimental data were analyzed using a randomized complete block design (RCBD). Critical differences between treatments were determined at a 5% significance level (Snedecor & Cochran, 1967).

Results

Natural Nest Characteristics of T. iridipennis

Wooden cavities and wall cavities were found to be the most common nesting sites for *T. iridipennis* colonies collected from various locations (Figure 2). Among the wall cavities, mud-brick and stone walls provide suitable nesting environments. Additionally, a few colonies were found in unconventional substrates such as clay pots, electric meter boards, and cement pipes (Figure 3). Significant differences ($p \leq 0.05$) were observed among natural nest characteristics such as entrance hole width (mm), cavity length, breadth, and height (cm), brood length and height (cm), and pollen pot length (mm) across colonies found in different substrates (Table 1). However, traits such as entrance height from the ground (cm), entrance hole length (mm), brood breadth (cm), honey pot length and breadth (mm), and pollen pot breadth (mm) did not differ significantly among nesting substrates.

Entrance Tube and Height from the Ground

A distinct entrance tube was absent in many nests, with only a small protrusion marking the entrance in several cases (Figure 2). Only two colonies, one nesting in a wooden log and another on an electric meter board, had well-developed entrance tubes. The height of the entrance tube from the ground varied between 39.33 cm and 163.33 cm depending on the location of the colony (Table 1), with an average height of 103.90 cm. The highest entrance was observed in the colony within the electric meter board (163.33 cm), while the lowest was found in a wooden log (39.33 cm). The average entrance tube dimensions were 4.38 mm in width and 8.57 mm in length (Table 1). The shortest entrance length (6.00 mm) was recorded in a wall cavity colony, whereas the longest (12.33 mm) was in a colony residing in an A. cerana hive. The narrowest entrance width (3.13 mm) was observed in a cement pipe, while the widest (6.67 mm) was found in a mud pot colony.

Cavity Size

The average dimensions of the nest cavities were 26.00 cm in length, 24.98 cm in breadth, and 15.27 cm in height (Table 1). Cavity sizes ranged from 16.67 to 38.00 cm in length, 15.00 to 33.67 cm in breadth, and 7.00 to 26.83 cm in height. The smallest cavity (16.67 × 15.00 × 7.00 cm) was found in an electric meter board, while the largest (38.00 × 33.67 × 26.83 cm) was found in a mud pot.

Brood Size

Brood chambers contained translucent, cylindrical, creamy-white eggs and exarate, C'-shaped pupae resembling sorghum seeds. The brood cells were 2.9–3.0 mm in width and 3.8-4.0 mm in height. Overall, brood sizes averaged 16.64 cm in length, 13.80 cm in breadth, and 10.13 cm in height (Table 2). Brood lengths ranged from 9.00 to 26.00 cm, breadths from 7.17 to 16.67 cm, and heights from 3.57 to 20.00 cm. The smallest brood (9.00 × 7.17 × 3.57 cm) was recorded in an electric meter board, while the largest (26.00 × 16.67 × 20.00 cm) was found in a mud pot colony.

Honey and Pollen Pots

Honey pot lengths ranged from 6.17 to 8.50 mm, and widths from 4.93 to 6.27 mm (Table 2). The shortest honey

Table 2. Natural nests of stingless bee colony found in different nesting substrate with brood, honey pots and pollen pots characteristics.

Colony	Brood size (cm)			Honey pots (mm)		Pollen pots(mm)	
	Length	Breadth	Height	Length	Breadth	Length	Breadth
Wall cavities	19.00 ± 3.46 ab	16.00 ± 7.00 a	14.00 ± 5.57 b	8.50 ± 0.10 a	5.93 ± 0.40 ab	8.13 ± 0.47 a	5.93 ± 0.55 a
Wooden logs	26.00 ± 5.29 a	16.33 ± 4.16 a	11.33 ± 5.03 bc	7.37 ± 0.38 abc	5.80 ± 0.30 ab	7.77 ± 0.42 ab	5.93 ± 0.38 a
Termite mounds	17.00 ± 8.19 bc	13.00 ± 3.00 ab	9.33 ± 3.06 bcd	7.17 ± 1.02 abc	5.87 ± 0.15 ab	7.37 ± 0.67 ab	5.77 ± 0.75 a
Cerena Hive	14.33 ± 2.52 bc	14.67 ± 2.08 a	7.17 ± 0.76 cd	7.23 ± 0.78 abc	4.93 ± 0.81 b	6.70 ± 0.62 b	5.43 ± 0.38 a
Cement Pipe	16.50 ± 1.32 bc	12.80 ± 0.72 ab	3.57 ± 0.12 d	6.17 ± 2.02 c	5.13 ± 1.21 ab	7.63 ± 0.55 ab	6.37 ± 1.10 a
Electricboard	9.00 ± 5.20 c	7.17 ± 5.06 b	5.50 ± 2.77 cd	6.50 ± 0.87 bc	5.67 ± 0.29 ab	6.60 ± 1.04 b	6.10 ± 0.85 a
Mud pot	14.67 ± 0.58 bc	16.67 ± 0.58 a	20.00 ± 1.73 a	8.17 ± 0.29 ab	6.27 ± 0.25 a	8.23 ± 0.25 a	6.40 ± 0.53 a
Mean	**16.64 ± 6.20**	**13.80 ± 4.53**	**10.13 ± 5.99**	**7.30 ± 1.14**	**5.66 ± 0.67**	**7.49 ± 0.80**	**5.99 ± 0.66**
F value	**3.95**	**2.17**	**8.54**	**2.16**	**1.81**	**3.26**	**0.72**
Sig. ($p \leq 0.05$)	**0.02**	**NS**	**0.00**	**NS**	**NS**	**0.03**	**NS**

pot (6.17 mm) was observed in a cement pipe colony, while the longest (8.50 mm) occurred in a wall cavity colony. The narrowest honey pots (4.93 mm) were found in an A. cerana hive, while the widest (6.27 mm) were recorded in a mud pot. Pollen pot lengths varied between 6.60 and 8.23 mm, and widths between 5.43 and 6.40 mm (Table 2). The shortest pollen pot length (6.60 mm) was found in an electric meter board colony, and the longest (8.23 mm) in a mud pot. Similarly, the narrowest pollen pots (5.43 mm) were recorded in an *A. cerana* hive, while the widest (6.40 mm) were found in a mud pot colony.

Development of trap nests for the stingless bee, T. iridipennis

The trap nest experiment was conducted in farmers' fields located within 1.5 km of an established *T. iridipennis* apiary. Among the treatments tested, smearing trap nests with stingless bee propolis proved to be the most effective attractant, outperforming both the stingless bee honey treatment and the untreated control (Figure 5). Among the seven trap nest types evaluated, reused *Apis cerana* hives attracted the highest number of swarms, followed by bamboo slits and wooden hives. In contrast, no swarms were attracted to cement pipes or plastic bottles under any treatment conditions. Bamboo slits and coconut shells coated with propolis demonstrated approximately threefold greater swarm attraction compared to the other trap nest types (Figure 5).

Hive Designs

Brood Volume of Colonies in Different Hive Designs

After eight months of observation, significant variations in brood volume were recorded among the different hive designs (Table 3). A consistent increase in brood volume was observed from September 2015 to May 2016, regardless of hive type. The rectangular box with two halves recorded the highest brood volume (2178.00 cm^3), followed by the modified UTOB hive (1406.80 cm^3). In contrast, the rectangular box with two compartments had the lowest brood volume (572.31 cm^3) (Table 3).

The percentage increase in brood nest volume from the initial to the final observation also varied by hive design. The rectangular box with two halves exhibited the highest increase (1861%), followed by the modified UTOB hive (1735%). The lowest increase in brood volume (1189%) was observed in the rectangular box with two compartments (Table 3).

Number of Honey Pots

The modified UTOB hive recorded the highest number of honey pots (24.68), closely followed by the rectangular box with two halves (24.13). The lowest numbers (20.26) were recorded in both the rectangular box with two compartments and the original UTOB hive (Table 3). The percentage increase in the number of honey pots from September 2015 to May 2016 also differed among hive types. The modified UTOB and the rectangular box with two halves showed the greatest increase (1134% and 1106%, respectively), while the UTOB and rectangular box with two compartments had the lowest increase (913%).

Number of Pollen Pots

Significant differences were also found in the number of pollen pots among the hive designs (Table 3). The rectangular box with two halves recorded the highest number of pollen pots (34.93), followed by the modified UTOB hive (32.06). The lowest number (28.04) was observed in the rectangular box with two compartments (Table 3). The highest percentage increase in pollen pots was found in the rectangular box with two halves (1064%), whereas the lowest increase occurred in the rectangular box with two compartments (834%).

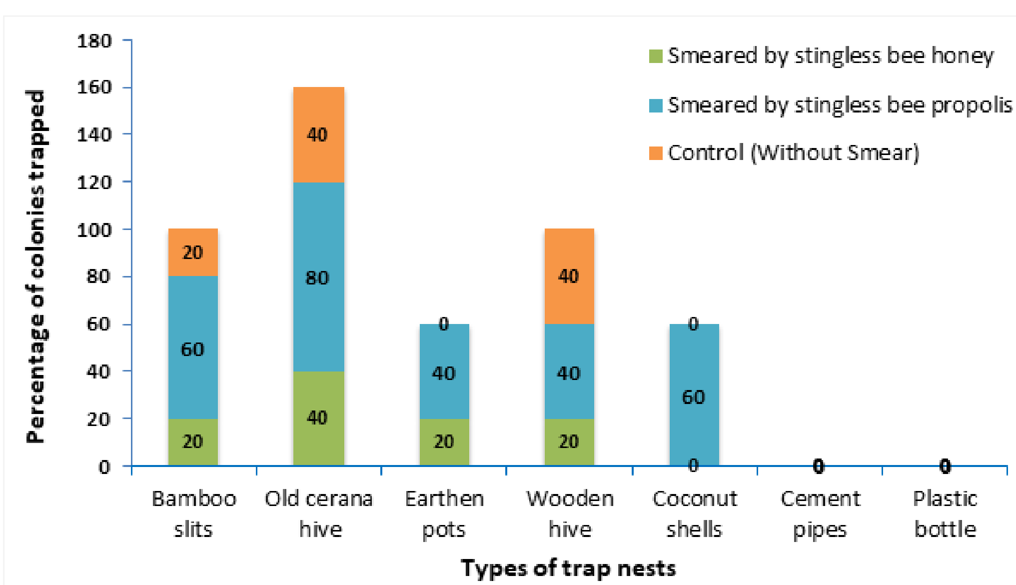

Fig 5. Percentage of colonies trapped in different types of trap nests used in farmers' fields.

Honey Pot Segregation

Segregation of honey and pollen pots from the brood area was observed in the UTOB hive and the rectangular box with two compartments (Table 3). In contrast, no such segregation was observed in the modified UTOB hive or the rectangular box with two halves. In the modified UTOB hive, honey and pollen pots were located adjacent to the brood cells within the brood chamber, and the upper story remained unused. In the rectangular box with two halves, the brood, honey, and pollen pots extended continuously into the adjoining chamber without any separation (Table 3).

Brood Nest Temperature in Different Hive Designs

The results indicated that brood nest temperature values in the initial month (September), the final month (February), and the overall mean did not differ significantly among the various hive designs (Figure 6). However, the highest brood temperatures were recorded in the modified UTOB and original UTOB hives, while the lowest values were observed in the rectangular box with two compartments. The mean brood nest temperature followed the trend: Modified UTOB hive > UTOB hive > Two-half hive > Two-compartment hive (Figure 6).

Table 3. Brood nest volume, number of honey pots (and their segregation), pollen pots, and their percentage growth over eight months in different hive designs.

Type of hive	Brood volume (cm^3)	Percentage growth	Number of Honey pots	Percentage growth	Number of Pollen pots	Percentage growth	Honey pot segregation
UTOB	1278.40^{bc}	1404^{b}	20.26^{b}	913^{b}	29.31^{b}	877^{b}	Found
Modified UTOB	1406.80^{b}	1735^{a}	24.68^{a}	1134^{a}	32.06^{a}	968^{a}	Not found
Two Compartments	572.31^{c}	1189^{b}	20.26^{b}	913^{b}	28.04^{b}	834^{b}	Found
Two Halves	2178.00^{a}	1861^{a}	24.13^{a}	1106^{a}	34.93^{a}	1064^{a}	Not found
SEm±	248.59		29.704		4.56		
CD (0.05 %)	766.03		3.097		14.04		
CV (%)	35.030		30.653		32.81		
F-test @ 0.05	*		*		*		

Note: each value is the average of 5 replications, NS - nonsignificant.

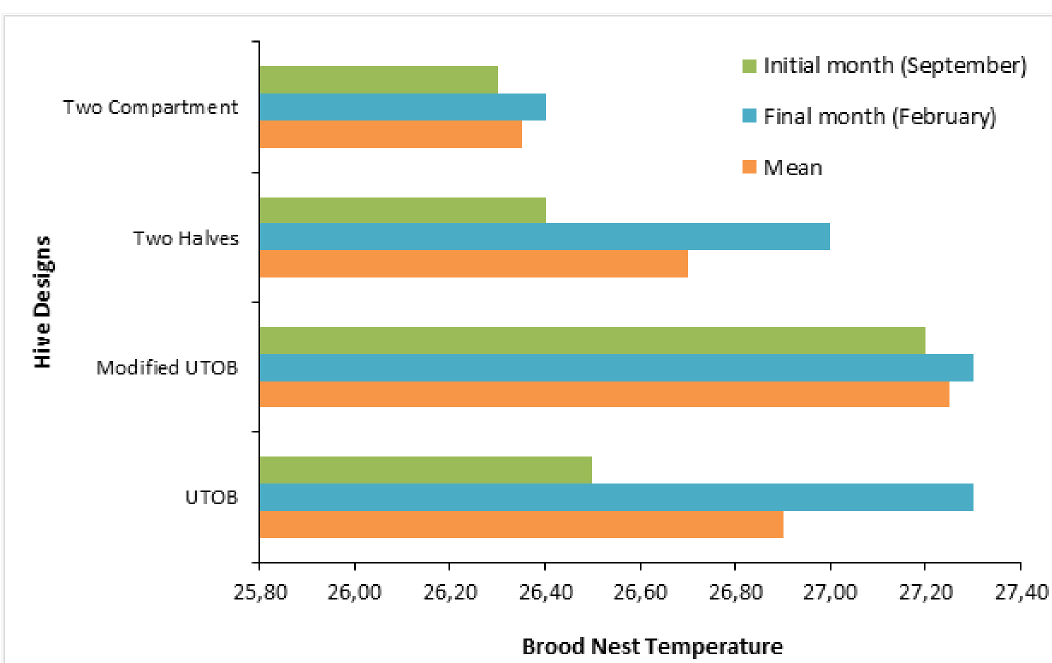

Fig 6. Brood nest temperatures in different types of hive designs.

Discussion

Natural Nest Characteristics of T. iridipennis

In this study, natural nests of *T. iridipennis* were observed in diverse locations, including wall cavities, wooden logs, mud pots, electric boards, termite mounds, and cement pipes. These bees consistently preferred enclosed cavities for nesting. Similar nesting site preferences were reported in earlier studies (Roopa, 2002; Danaraddi et al., 2009; Bhatta et al., 2019).

Entrance Tube and Height from Ground

A distinct entrance tube was absent in many nests; instead, a small entrance protrusion was typically observed. The areas surrounding the entrance hole were often heavily coated with resin droplets, presumably as a defense against intruders. These observations align with those of Chinh et al. (2004) and Pavithra et al. (2012), who reported both the presence and absence of entrance tubes in stingless bee nests. The height of nest entrances varied depending on the location of the cavity, ranging from wooden logs to brick or cement walls, consistent with findings from Danaraddi et al. (2009).

Cavity Size

The size of cavities used for nesting varied significantly in terms of length, width, and height. This contrasts with the findings of Chinh et al. (2004), who reported that *Lisotrigona carpenteri* in Vietnam occupied relatively small cavities, with volumes ranging from 200 to 1000 cm^3. These differences may be attributed to species-specific preferences, geographic location, and climatic conditions.

Brood Size

Brood cell sizes varied significantly across nests found in different substrates. Broods were tightly clustered, typically leaving a 2-3 cm gap between the outermost cells and the cavity wall. These cells were structurally distinct from the surrounding honey and pollen pots. A similar compact brood arrangement was reported by Gajanan et al. (2005), though slight variations in brood cell size were noted. Such differences are likely due to geographic variation or differences in species studied.

Honey and Pollen Pots

Honey pots were circular, dark brown, and slightly larger than the pollen pots, which were occasionally interspersed among them. The honey pots ranged from 6.17 to 8.50 mm in length and 4.93 to 6.27 mm in breadth. These measurements are consistent with earlier findings (Roopa, 2002; Danaraddi et al., 2009). Pollen pots, composed of soft cerumen, were oval-shaped and sealed after being packed with pollen granules. Only a few open pots were available for incoming pollen. The pollen pots measured between 6.60 to 8.23 mm in length and 5.43 to 6.40 mm in breadth, again matching previous reports.

Development of Trap Nests for T. iridipennis

Among the seven types of trap nests tested, old *Apis cerana* hives were the most successful, followed by bamboo slits. Propolis smearing proved more effective than honey in attracting stingless bee swarms. In some parts of the Western Ghats, bees have colonized electric boxes due to habitat loss caused by urban development. Natural nesting substrates such as tree trunks, termite mounds, and earthen pots have declined, leading to human-bee conflicts. In response, people often resort to destructive methods, such as using pesticides or fire, to eliminate colonies. Trap nests offer a sustainable solution, providing alternative nesting options and mitigating conflict. Some trap nests – like those made from cement pipes and plastic bottles – failed to attract swarms, likely due to the study's short six-month duration and the species' inherently slow and infrequent swarming behavior (Veen & Sommeijer, 2000; Slaa, 2006). The limited swarming observed may also be due to the availability of natural nesting substrates in coffee agroforestry systems and forest groves. In a 2021 farmer survey, old A. cerana hives and coconut shells emerged as popular trap nest materials. Of 50 coconut shells placed, 16 (32%) attracted colonies. Additionally, 9 out of 20 hives (45%) previously abandoned by *A. cerana* were colonized by stingless bees within a month, suggesting that wax and comb debris serve as attractants. A similar study by Oliveira et al. (2013) in Brazil reported 61 swarms of nine stingless bee species captured using trap nests.

Hive Designs

Brood Volume in Different Hive Designs

A comparative analysis of four hive designs revealed that the rectangular box with two halves supported the fastest colony development, while the two-compartment rectangular box showed the slowest growth. The modified UTOB and original UTOB hives showed moderate growth rates (Figure 4; Table 3). The percentage increase in brood volume was highest in the two-half hive and lowest in the two-compartment hive. In contrast to Roopa (2002), who observed a 29.74% decline in colony weight between October and January, all hive designs in the present study showed a gradual increase in brood volume. This discrepancy may stem from unknown environmental or biological factors. The enhanced growth in the two-haves hive likely results from greater internal space facilitating brood proliferation.

Number of Honey and Pollen Pots

The percentage growth in the number of honey and pollen pots varied across hive designs. The rectangular box with two halves again showed the highest increase, while the two-compartment box had the lowest. The likely reason for the latter is internal compartmentalization, which slows expansion – bees tend to fill one compartment before expanding into the next. If resources or environmental conditions are limited, they may never complete the second compartment. In contrast, the two-half hive's open design allows bees to simultaneously construct brood cells and store honey and pollen. Modified UTOB hives and the two-half hives thus recorded more honey pots (Sommeijer, 1999; Bayeta & Hora, 2021), with similar observations reported for split bamboo hives (Kumar, 2012).

Honey Pot Segregation

Despite favorable growth rates in the two-half and UTOB hives, neither design supported honey pot segregation – a feature crucial for hygienic honey harvesting. Further research should focus on developing hive designs that support both brood growth and spatial separation of honey pots.

Brood Nest Temperature

To evaluate whether stingless bees thermoregulate their nests like *Apis* species, brood nest temperatures were recorded across hive designs. The differences were not statistically significant (Figure 4), indicating that *T. iridipennis* can maintain nest temperatures regardless of hive design. The observed brood nest temperature differed by approximately 5 °C from Engels et al. (1995), who reported 32 ± 3 °C. This variation may reflect differences in species, geography, and climate (Macías-Macías et al., 2011). Rasmussen (2013) noted that most stingless bees in South India are identified as *T. iridipennis*, though several other species exist, including *T. praeterita*, *T. ruficornis*, and *T. bengalensis*. Molecular studies have yet to clarify whether these are distinct or synonymous species (Charanakumar et al., 2022; Gyeltshen et al., 2024).

Conclusion

This study investigated the nesting behavior, productivity, and environmental preferences of *T. iridipennis* to inform hive and trap nest design. Among trap nests, old *Apis cerana* hives were most effective, followed by bamboo slits, wooden hives, and coconut shells. Field experiments showed that the rectangular box with two halves supported the highest brood volume and the greatest number of honey and pollen pots, although it lacked honey pot segregation. The two-compartment hive showed the poorest performance across all metrics. These findings offer valuable guidance for stingless beekeepers and conservationists and highlight the importance of designing hives that support both productivity and sustainable harvesting practices and lay a foundation for further research and conservation efforts in the Western Ghats and other regions in the Indian subcontinent.

Author's Contributions

Imran Ali: Formal analyses, investigation & writing-original draft.
R.N. Kencharaddi: Conceptualization, investigation, writing-original draft, writing-review & editing.
Charanakumar: Methodology, investigation, formal analyses, writing-original draft.
Chet P. Bhatta: Methodology, writing-original draft, writing review & editing.
S. Dinesha: Writing-original draft, writing-review & editing.

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Data availability

Data is available on request.

Declaration of Competing of Interest

All authors declare that they have no conflict of interest. The work represents original research carried out by the authors.

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