https://doi.org/10.17576/serangga-2026-3102-08

EFFECTS OF HIVE MATERIAL CHOICE ON COLONY HEALTH AND PERFORMANCE OF *Apis cerana* F. IN TROPICAL CLIMATES

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Received: 25 November 2025; Accepted: 11 July 2026; Published: 23 August 2026

ABSTRACT

The honey bee (*Apis cerana* F.) is widely distributed across Asia and is the main domesticated honey bee species in rural Sabah, Malaysia. Although it is of significant importance, colonies of *A. cerana* F. are extremely sensitive to changes in the tropical environment. This means that the hive material is important to maintaining healthy, productive colonies. This study was carried out at the Insectarium, Faculty of Sustainable Agriculture (FSA), Universiti Malaysia Sabah (UMS) to examine the performance of *A. cerana* F. colonies housed in three different kinds of hive, namely *Shorea* sp. (4 replicates), *Dipterocarpus* sp. (4 replicates), and plywood (4 replicates). The colony's performance was evaluated over more than 24 weeks by analysing worker bee development and brood comb development. Abiotic factors, including hive temperature, relative humidity, and wood moisture content, were also recorded. This revealed that the colonies in the hives of *Shorea* sp. reared more worker bees and had more brood combs than the other hive types. *Shorea* sp. also provided the best internal microclimatic conditions, suggesting that the choice of hive wood type greatly affects colony performance. This discovery highlights that the appropriate hive material is critical for good tropical honey bee management.

Keywords: Abiotic factors; *Apis cerana* F.; colony performance; hive wood type; tropical honey bee

ABSTRAK

Lebah madu (*Apis cerana* F.) biasa dijumpai di kebanyakan negara Asia dan merupakan spesies lebah madu yang paling banyak diternak di kawasan luar bandar Sabah, Malaysia. Walaupun ianya penting, koloni *A. cerana* sangat sensitif terhadap perubahan persekitaran tropika, menjadikan pemilihan bahan sarang adalah penting untuk mengekalkan kesihatan dan produktiviti koloni. Kajian ini telah dilaksanakan di Insektarium, Fakulti Pertanian Lestari (FPL), Universiti Malaysia Sabah (UMS) untuk menilai prestasi koloni *A. cerana* yang ditempatkan dalam tiga jenis sarang: *Shorea* sp. (4 replikasi), *Dipterocarpus* sp. (4 replikasi), dan papan lapis (4 replikasi). Sepanjang 24 minggu, prestasi koloni dinilai melalui perkembangan lebah pekerja dan pertumbuhan sisir anak-anak lebah, manakala parameter abiotik seperti suhu sarang, kelembapan relatif, dan kandungan kelembapan kayu turut direkod. Hasil kajian menunjukkan bahawa koloni dalam sarang *Shorea* sp. secara konsisten menghasilkan lebih banyak lebah pekerja dan sisir anak-anak lebah berbanding jenis sarang lain. *Shorea* sp. juga menyediakan keadaan mikroklimatik dalaman yang paling sesuai, menunjukkan bahawa pemilihan kayu sarang memberi pengaruh besar terhadap prestasi koloni. Penemuan ini menekankan kepentingan pemilihan bahan sarang dalam mengoptimumkan amalan pengurusan lebah madu tropika.

Kata kunci: Faktor abiotik; *Apis cerana* F.; prestasi koloni; jenis kayu sarang; lebah madu tropika

INTRODUCTION

Apis cerana F., commonly known as the Eastern or Asian honeybee, is a very important pollinator as well as a honey producer (Aslan et al. 2016; Hung et al. 2018; Qu et al. 2025). It plays an ecological and economic role in pollinating a variety of crops and wild plants, contributing to agricultural output and biodiversity. In Malaysia, especially in Sabah, *A. cerana* F. remains the foremost village bee in rural communities, with beekeeping activities contributing to improved sustainable livelihoods and generating supplementary income (Ahmad & Shamsudin 2013).

Like *Apis dorsata* F. and *Apis mellifera* L., which have a regular three-rank social structure: queen, workers and drones (Yadav et al. 2017). The queen's function is to produce eggs for the colony (Jasmi et al. 2020). Meanwhile, the worker bees do the colony's most critical chores: foraging, brood care, housekeeping, hygiene, and nest-building. Drones exist solely for reproduction, mating with virgin queens from their own or neighbouring colonies (Koeniger et al. 2005). If they did not have this caste-system division, the hive would be unproductive and unable to cope with shifting environmental stresses.

Apis cerana F. can nest in a variety of wild and managed sites, depending on the substrate conditions within the brood chamber (Hung et al. 2018). They nest in hollow tree stems and in man-made hives. In such nests, the bees build complex, multi-layered honeycombs consisting of hexagonal cells of beeswax, serving as both honey/pollen storage and brood-rearing space. Temperate species, however, are not so flexible; tropical *A. cerana* F. tends to abscond more. Physiological stress, scarcity of resources, and environmental disturbances are among the major factors causing colony absconding in *A. cerana* F. (Aryal 2020). While absconding is a creature-comfort survival act, the persistent trend of absconding may provide significant insights into the presence of other, more serious pest or disease challenges, or into microclimates within the hive that are not suitable for honeybee survival

(Bruckner et al. 2023). This tendency to abscond is further complicated by the availability of other cranes and alternative nesting sites and foraging opportunities throughout the year in the favourable tropical climate of Sabah.

Beekeeping is widespread throughout Asia (Roziah et al. 2024; Siti Asma' et al. 2024); however, the effects of various hive-building materials, especially wood type, on honeybee performance remain underexplored. This gap is significant because the hive materials regulate the internal microclimate, which in turn affects the thermoregulation, productivity, and survival of colonies (Erdoğan 2019). An observation revealed that traditional apiculture practice in Malaysia uses materials that simulate bees' natural nesting habitat. These are from hollowed trees, from trees with fabricated hive parts made from wooden boxes, and from large bamboo tubes, which in Sabah are most commonly used as *Gigantochloa levis* (local name buluh tampung) and *Bambusa vulgaris* (local name buluh minyak) (Koeniger et al. 2005). Although materials such as those afford cavities similar to those found in nature, their capacity to support colony performance has not been scientifically tested.

At the national and international levels, Sabah, Borneo, has the potential to produce various honey bee products, such as honey, propolis, and royal jelly, for mass production (https://kpd.sabah.gov.my/). However, knowledge of optimal hive wood types is limited, which is a drawback to the development of efficient and sustainable beekeeping practices (Koeniger et al. 2011). Similarly, hives made of wood had no impact on the performance of *A. mellifera* L. colonies in the study conducted by Aishwarya et al. (2022). They also reported that teak hives yielded better results than other wood types, which is attributed to teak's natural insulating properties. Jagadeesan et al. (2022) noted that the cellular structure of wood helps regulate temperature and humidity, thereby stabilising the hive's ambience. Hence, similar effects may be inferred for tropical *A. cerana* F. populations in Sabah, Borneo, although scientific evidence remains limited.

The microclimate in managed honeybee colonies is very variable in tropical areas. The climate (air temperature and humidity) changes hourly, which directly affects brood (so brood development may be disrupted several times). This stress is increased in uninsulated hives; the bees are compelled to expend some of their precious and fundamental metabolic energy to regulate conditions inside the hives, resulting in neglected larval care (Erdoğan 2019). The research carried out by Muhammad Shakir et al. (2022) in Jerantut, Pahang revealed that the colony collapse in *A. cerana* F. may be attributed to a detrimental hive microclimate, a lack of food sources, and high levels of pest attacks. It is therefore necessary to address systemic weaknesses through the careful selection of materials used in hive construction, so that these can be considered not only as management variations but also as product-foraging factors, thereby constituting a survival factor for the colony.

The aim of this research was to determine the effects of certain hive wood types and respective microclimates on the health and performance of *Apis cerana* F. colonies. The investigation examined the development of worker bees and brood production as the two most important factors in the positive growth of colonies. This study systematically compared different wood types as hive construction materials to optimise hives for tropical beekeeping, thereby improving colony management and sustainable beekeeping practices in Malaysia.

MATERIALS AND METHODS

Study Location and Duration

The research was conducted at the Insectarium, Faculty of Sustainable Agriculture (FSA), Universiti Malaysia Sabah (UMS), Sabah, for 16 months, from October 2021 to January 2023. This period included the transport of honeybee colonies from Kota Marudu to Sandakan, material procurement, hive construction, colony establishment, acclimatisation, and testing and monitoring of the colonies.

Hive Preparation

The hives were built from locally available materials, and both traditional and modern beekeeping practices were used in Sabah. To ensure that all wood and plywood were of the same quality, the materials were sourced from a single local manufacturer in Sandakan. *Shorea* spp. and *Dipterocarpus* spp. were chosen because of their widespread occurrence and common use in rural apiculture, owing to their durability and natural insulating properties. Plywood, widely used today in beekeeping for its low cost and ease of workability, served as a control. The hives are made to a common size, with standardised entrance, frame, and wall thicknesses, following @Hasbulah et al. (2021). This standardisation makes it possible to conclude that any differences in colony performance are due to the type of wood utilised rather than to structural variations.

Species Identification and Colony Sourcing

Apis cerana F. specimens were carefully collected from colonies supplied by local rural farmers under Korporasi Pembangunan Desa Sabah (KPD), Kota Marudu, Sabah, Malaysia, and the specimens were classified as worker bees. Mounted and preserved specimens were sent for taxonomic confirmation using standard methods based on Karunaratne & Edirisinghe (2008) and Koeniger et al. (2005). After species identification, 12 experimental colonies were established, with four replicates (hives), each of *Shorea* sp., *Dipterocarpus* sp., and plywood.

Colony Standardisation and Acclimatisation

To reduce genetic and environmental confounding variables, the genetics of all colony stocks were stabilised through two months of acclimatisation at the new apiary location. This period was very important for establishing a natural activity pattern before the production of new queens and sufficient workers that could be used for the experiments. In the final evaluation, it was ensured that sister queens from the same lineage were reared and introduced into the new hives to boost their egg-laying capacity and ensure genetic consistency. Each experimental unit was then a natural colony consisting of workers, drones, and a single laying queen of about two to three weeks of age, as the presence of eggs and larvae confirmed the queen's reproduction. Colonies were then transferred to their respective wood-type hives, and a final two-week stabilisation period was used to minimise transfer stress. No supplementary feeding was possible, as all food was to be obtained from the environment to avoid impacting colony performance.

Experimental Design

A total of 12 hives, 4 hives per material, for three different materials were established at the Insectarium, FSA, UMS. The *Apis cerana* F. colonies were studied in the hives made from *Shorea* sp., *Dipterocarpus* sp. and plywood. All the hives were started with seven frames: five clean and two containing worker bees, drones, and newly hatched sister queens of the same age group. All hives were kept under the same conditions, with the bottom painted black and zinc roofing, and sides shaded with black netting, with the individual hives 1.5 m apart (see

Figure 1). This setup was adopted for all colonies; whether it housed four, six, or eight, it allowed the colonies to be shaded from direct sunlight and to have the same environment for all treatments. Throughout the 24 weeks (plus 2 weeks acclimatisation after transfer to the new hives), positions were not changed to enable consistent checking of the effects of the materials. To reduce environmental variability, all colonies were handled using standard beekeeping practices, including daily inspections and routine pest and disease management. If a colony absconded, it was recorded, and the colony was recaptured and returned to the hive type assigned to the experiment to maintain experimental integrity. During this study, the absconded colonies were all recaptured and returned to their respective hive types to preserve experimental uniformity. When a colony predisposed to abscond did so five times without building up the brood combs during the experiment, the occasion was sometimes termed absconding for internal unfavourable hive conditions.

Figure 1. Hives were placed 1.5 m apart under zinc roofing, with the side areas covered with black netting shade to ensure uniform exposure and facilitate colony monitoring

Data Collection

Assessment of worker bees and brood development

The colony performance was measured by directly determining the percentage of combs covered by the five initially broodless frames, with comb coverage defined as the percentage of comb area containing worker bees and brood (both capped and uncapped cells). Weekly assessments were conducted using visual inspection under natural light to assess colony strength and reproductive activity of each target frame (Figures 2 & 3). The percentage values were grouped into a five-grade semi-quantitative evaluation system (Table 1) to facilitate evaluation and enable a somewhat quantitative comparative evaluation of the colonies from one type of hive to the other. Rank 1 indicated almost complete coverage (≥81%), and rank 5 was barely occupied (1% or less). Figures 2 and 3 illustrate typical combs showing where worker bees are located and where the brood is in various stages of development, respectively, as visual reference for each category. These frames were recorded and ranked between 1 and 5 (low to high) from Week 1 to 24. Classification based on Kasangaki et al. (2018), modified according to *Apis cerana* F. in the tropical environment of Sabah.

Table 1. Rank and categories according to the percentage of honeycomb area covered by worker bees and brood in each hive

Rank	**Percentage of Area Occupied by Worker Bees and Brood on the Combs**
1	≥81%
2	≥61%
3	≥41%
4	≥21%
5	≥1%

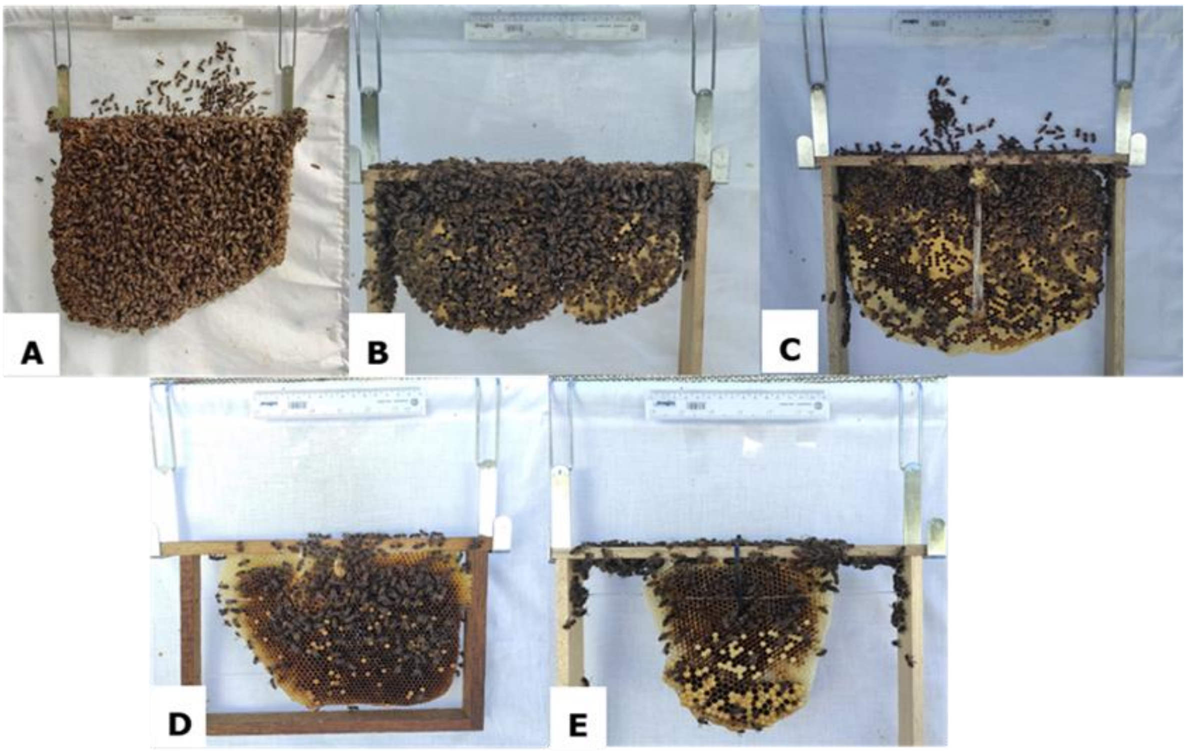

Figure 2. Comb surface occupied by adult workers bee (A) Rank 1 (≥81%), (B) Rank 2 (≥61%), (C) Rank 3 (≥41%), (D) Rank 4 (≥21%), (E) Rank 5 (≥1%)

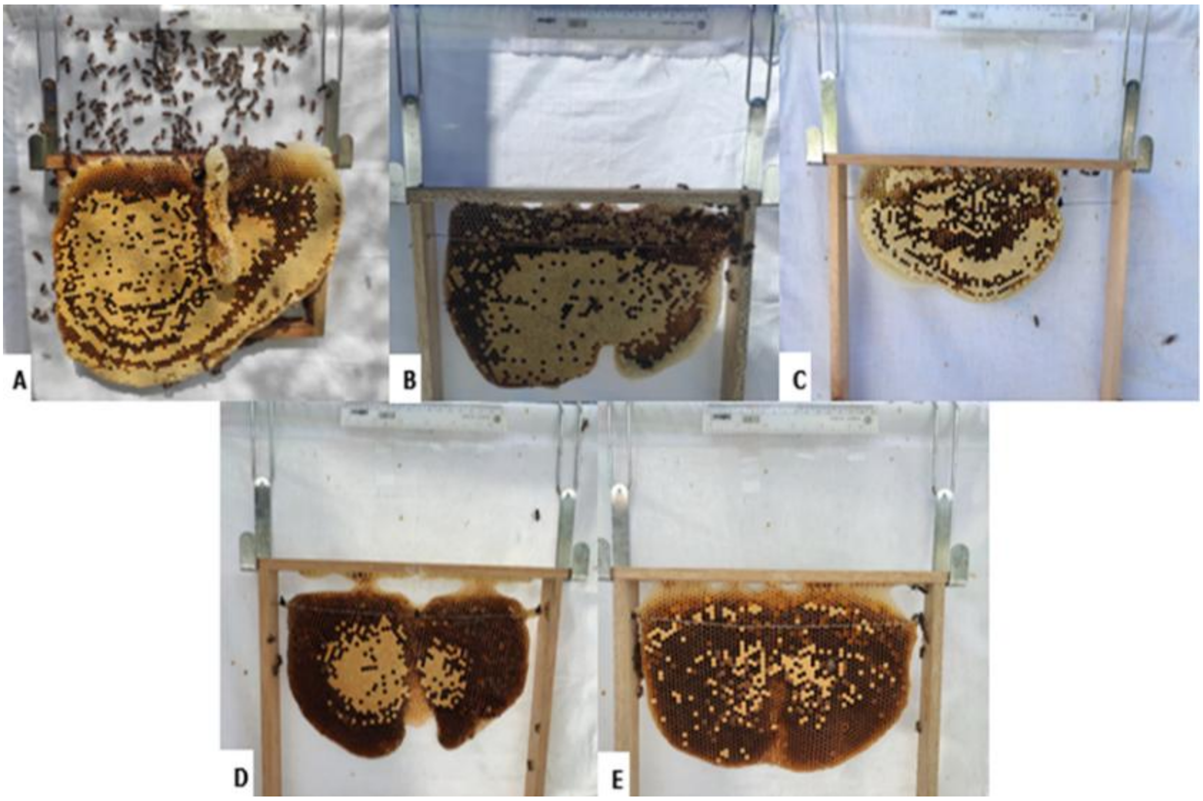

Figure 3. Comb surface occupied by bee brood (A) Rank 1 (≥81%), (B) Rank 2 (≥61%), (C) Rank 3 (≥41%), (D) Rank 4 (≥21%), (E) Rank 5 (≥1%)

Environmental factors

The internal hive (Brood chamber) temperature (°C) was recorded using digital thermometers placed in the central part of the brood chamber. At the same time, the relative humidity (RH, %) was measured using a MASTECH MS6900 digital psychrometer to ensure homogeneous environmental conditions across replicates. The moisture content of the wood (%) was measured as a physical characteristic of the hive materials three times a week (in the morning, noon, and evening) over a 24-week period using a portable moisture meter (Habotest HT633). All microclimatic and material data form a holistic foundation for understanding how hive material properties influence the internal colony environment and colony development.

Statistical Analysis

Initial testing for normality and homogeneity of variances was performed on the data to determine if the use of various hive materials had a significant impact on: 1) Colony performance, and 2) abiotic factors. Data for which parametric assumptions were violated were analysed using the Kruskal-Wallis H test, while those for which the data were normally distributed and had homogeneous variances were analysed using a one-way ANOVA test. Interquartile ranges (IQRs) and percentage breakouts by rank were reported for nonparametric data to adequately demonstrate variability/dispersion. A lower IQR indicates that individuals within brood regions and experimental units are more evenly developed and exhibit greater localised stability of workers. The significance level was set at *$P<0.05$*. However, if significant differences in parameters were found in the dataset, post hoc analyses (Tukey's B test) were used to identify specific differences between hive types. Such a methodology enabled the detection of differences, including pairwise differences, in abiotic parameters such as temperature, humidity, and wood moisture content.

RESULTS AND DISCUSSIONS

Determination of Bee Combs, Worker Bees, and Brood in Hives of Different Wood Types
The growth of worker bees was significantly different between the three types of hive material (Table 2; Kruskal-Wallis H-test, H = 6.15, n = 60, P = 0.05, ε^2 = 0.104). The hives of *Shorea* sp. had a significantly higher percentage of the frames covered by combs (more than 81% of the comb area) than both the *Dipterocarpus* sp. hives and the plywood hives, the latter of which had none over 81% covered (n = 0, 0%). In contrast, the highest percentage of frames free from combs (n = 7, 35%) was recorded in the plywood hives, followed by *Dipterocarpus* sp. hives (n = 5, 25%) and *Shorea* sp. hives (n = 3, 15%). Based on these results, a preference for wood type is evident, with *Shorea* sp. hives supporting a higher density of worker bees.

The Kruskal-Wallis H-test showed that there were significant differences between brood development of the three types of hive materials (H = 7.16, n = 60, P = 0.03, ε^2 = 0.121). Colonies housed in *Shorea* sp. hives had a higher percentage of brooded combs (n = 8, 40%) compared to *Dipterocarpus* sp. and plywood colonies, which did not have any brood expansion on the experimental frames (n = 0, 0%). The highest percentage of frames with brood was for Plywood hives (n = 7, 35%), followed by *Dipterocarpus* sp. (n = 5, 25%) and *Shorea* sp. (n = 3, 15%). The results here show that the hives of *Shorea* sp. can result in better brood production, thus yielding a better overall colony performance when compared to their own colonies in hives made from *Dipterocarpus* sp. and plywood hives.

This study showed that colonies with hives of *Shorea* sp. performed better than those reared in hives constructed from *Dipterocarpus* sp. and plywood, as exemplified by the significant differences in the number of worker bees, the brood area and uniformity of bee development in the preferred material ($P \leq 0.05$; Table 2). A smaller interquartile range (IQR) indicates greater developmental consistency and stability in worker populations and brood areas. This uniformity was marked in the case of *Shorea* sp. hives (worker IQR = 1.00, 2.00, brood comb IQR = 1.00, 2.00) as opposed to the hives of *Dipterocarpus* sp., which exhibited wider variations. (worker IQR: 0.75, 4.75; brood comb IQR: 0.75, 4.00) and plywood hives (worker IQR: 4.00, 5.00; brood comb IQR: 0.75, 4.00).

Table 2. Percentages (%) of worker bee combs and capped brood combs across different rank categories in hives made from three wood types, with four replications and seven frames, monitored over 24 weeks

Percentages (%) Of Bee Combs	**Beehive Types**	**Total Frames (N)**	**Rank Categories (Total And %)**						**IQR (25 – 75)**
			≥81%	**≥61%**	**≥41%**	**≥21%**	**≥1%**	**0%**	
Worker's Bee	Plywood	20	0 0%	0 0%	1 5%	4 20%	8 40%	7 35%	4-5
	Shorea sp.	20	5 25%	10 50%	0 0%	2 10%	0 0%	3 15%	1-2
	Dipterocarpus sp.	20	0 0%	0 0%	7 35%	3 15%	5 25%	5 25%	0.75-4.75
Brooded Combs	Plywood	20	0 0%	0 0%	4 20%	2 10%	7 35%	7 35%	3-5
	Shorea sp.	20	8 40%	7 35%	2 10%	0 0%	0 0%	3 15%	1-2
	Dipterocarpus sp.	20	0 0%	0 0%	7 35%	4 20%	4 20%	5 25%	0.75-4

Note: IQR = Interquartile Range. A smaller IQR indicates a higher percentage of workers and brood development in honeybees.

The increment in brooded comb area is a known indicator of a healthy colony, according to Erdoğan (2019). Worker bees have important functions in protecting the nest, finding food and controlling the temperature. In this study, adult workers were observed huddling and moving from the outer frames to the center at night and when it was raining heavily, using honey to generate heat for the brood nest, consistent with Erdoğan's (2019) behavioural studies. Also, capping by honeybees is an important natural phenomenon that helps stabilise the nest through thermoregulation, protection of brood, sealing of honey stores, and structural reinforcement of the comb plate (Wakgari & Yigezu 2021). The finding of one hive with a higher proportion of capped broods in the *Shorea* sp. colonies indicates better colony fitness and developmental success, as colony growth is related to achieving a threshold worker population for transitional change from resource maintenance to active reproduction (Ma et al. 2023). Table 2 indicates that colonies in *Dipterocarpus* sp. and Plywood had higher interquartile ranges (IQRs) for brood development and worker population, respectively, indicating smaller populations. This decreased performance could be due to the volatile organic compounds (VOCs) released from the wood interfering with the process. Olfactory cues play a significant role in the lives of honeybees, among them those that can be provided by hive materials (Reinhard & Srinivasan 2009). Pheromones play an important role in social communication, reproductive regulation, and behavioural manoeuvres within colonies (Paoli & Galizia 2021). Therefore, physiological stress, miscommunication between colonies, and behavioural problems may occur when strong or pungent scents from certain woods, such as Dipterocarpus sp., or from adhesive materials, such as plywood, interfere with the chemical information being transmitted from one colony to another. However, more research is required to understand exactly how these disruptive odours occur in tropical honeybees.

This study has shown that retarded brood production and comb coverage are signs of inferior performance of the colony in plywood hives (Table 2). Another important area of study involves the release of volatile organic compounds (VOCs), especially formaldehyde, from man-made adhesives in new plywood. Further, the hives were purchased directly from a local manufacturer, so in this case, active degassing of adhesives was likely to have been high, leading to high VOC exposure early in the hives' lives. Although significant VOC emissions have been found in airtight indoor environments (Cao et al. 2019), the evaluation of such emissions under outdoor conditions was not conducted in this study, as they would occur in apiaries. However, conversations with local beekeepers have confirmed these observations: *Apis cerana* F. prefers aged, weathered plywood to new plywood, with the usual result being absconding from their hives. Further studies should include in vivo measurements of VOC concentrations in hives to assess whether these emissions cause stress in the colonies. In addition, earlier research has demonstrated that properties of hive materials and thermodynamics play an important role in both the growth of the colonies. For instance, Heidarzabeh and Esteghamat (2016) observed the colony size and honey production of colonies with different insulating materials such as plywoods, and long-term colony development was significantly influenced by different wooden materials and their insulating properties (Iqbal et al. 2026).

The conclusions of this study highlight the critical need to select appropriate hive materials for tropical beekeeping. However, it is important to remember that honeybees are highly sensitive to volatile organic compounds, and strong odours in hive structures may compromise colony stability. Overall, hives made of *Shorea* sp. provide favourable microenvironmental conditions that support colony growth and performance. On the other hand, strong natural odours from *Dipterocarpus* sp. and newly manufactured plywood hives may have a repellent effect on the colony and increase the risk of absconding, but more study is needed to support this claim.

Temperature (°C), Relative Humidity (%) and Wood Moisture Content (%) in Beehives of Different Wood Types Measured For 24 Weeks

The wood moisture content of the three types of hives was significantly different (one-way ANOVA, $F_{2,215} = 504.9$, *P<0.001*). The average moisture content for *Shorea* sp. hives was the lowest (11.22%), followed by the Dipterocarpus sp. hives (12.97%) and last by the plywood hives (13.61%), as shown in Table 3. However, there was also a significant difference in the wood temperature between the different types of hive (one-way ANOVA $F_{2,215} = 21.41$, *P<0.001*). The average temperatures of the hives were 34.87 °C in *Shorea* sp. hives, 33.33 °C in *Dipterocarpus* sp. hives, and 32.88 °C in plywood hives. Also, there were significant differences in relative humidity (%RH) between hive types (one-way ANOVA; $F_{2,215} = 47.34$, *P<0.001*). The mean RH in the *Shorea* sp. hives (63.89%), *Dipterocarpus* sp. hives (58.81%), and plywood hives (56.23%) were highest, very high, and high, respectively.

Table 3. Mean and standard error (SE) of wood moisture content (%), temperature (°C), and relative humidity (RH) in beehives, measured three times a week over 24 weeks

Microclimate	**N**	**Beehives (Mean & SE)**		
		***Shorea* sp.**	***Dipterocarpus* sp.**	**Plywood**
Wood Moisture Content (%)***	216	11.22^{a} (0.057)	12.97^{b} (0.068)	13.61^{c} (0.034)
Temperature (°C)***	216	34.87^{a} (0.33)	33.33^{a} (0.13)	32.88^{b} (0.13)
Relative Humidity (RH, %)***	216	63.89^{a} (0.76)	58.81^{b} (0.59)	56.23^{c} (0.21)

Note: Asterisks *** indicate significance at *P<0.001*. Different superscript letters indicate a significant difference (*P>0.05*) between the samples and the standards, as determined by Tukey's b. Values with at least one identical letter in the same row are not significantly different (*P>0.05*).

Temperature, relative humidity (RH), and wood moisture content are important abiotic factors to consider when assessing the performance of a honey bee colony. The downside of this study is that no outdoor temperature or humidity data were collected alongside the data from inside the hives. Whilst all hives were kept under similar site conditions, in future it would be beneficial to include external environmental data, which would better isolate hive-specific effects from overall site environmental fluctuations. Abou-Shaara et al. (2017) indicated that the optimal mean temperature for *Apis mellifera* colonies is between 33 and 36°C. Average temperature for all types of hives in the present study ranged from 32.88 to 34.87°C (Table 3), which is somewhat different from the optimum temperature range for the efficiency of *A. cerana* F. worker bees in India (34–34.5°C) as reported by Mangle (2020). Honey bees are ectothermic, meaning they rely on ambient temperature to regulate their internal body temperature (Coulibaly et al. 2022). It is important to keep hive internal temperatures sufficient, especially in the brood chamber, as temperatures within or below the brood can retard larval development or increase mortality rates (Daniel et al. 2022; Stabentheiner et al. 2010; Zeng et al. 2020). In this research, hives containing *Shorea* spp. showed the highest mean temperature level (34.87°C), which might be responsible for making their colony performance better than that of *Dipterocarpus* spp. and plywood hives (Tables 2 & 3). It is important that hives maintain stable thermal conditions, and studies by Cook et al. (2022) found that smaller hives had lower average temperatures and greater thermal fluctuations.

The relative humidity (RH) is vital for brood development because appropriate RH levels can help prevent desiccation of brood cells and enhance larval viability (Abou-Shaara et al. 2017). Several studies (Ellis et al. 2008, 2010) showed that optimal RH in the brood ranges from 55% to 90%, generally 60%. Human et al. (2006) found an increase in RH in areas with nectar stores. The hive RH in the present study ranged between 56.23 and 63.89%, which is within these ranges and is favourable for creating a stable environment for the development of the colony in the tropical climate.

Wood moisture significantly affects the microclimate inside the hive and, consequently, the colony's health (Suksuwan et al. 2023). The wood moisture content for the different types of hives was between 11.22% and 13.61% (Table 3). However, hives made from *Shorea* sp. had the lowest moisture content of 11.22%, while those of *Dipterocarpus* sp. and plywood had 12.97% and 13.61% moisture content, respectively. Reducing moisture in the wood is beneficial because it limits the ingress of excess moisture into the hive, thereby favouring the stabilisation of ambient relative humidity and brood development (Cecchi et al. 2020). Too much moisture can cause fungi to thrive, and too little moisture can cause harm to capped brood (Ellis et al. 2010). Thus, *Shorea* sp. wood with low moisture content is more favourable for a healthy colony and results in better productivity.

Wood will naturally reach an equilibrium moisture content (EMC) with its surrounding environment through the uptake or release of water until it reaches EMC (Bartolucci et al. 2021). According to Mitchell (2018), EMC may change by 1% depending on the RH in the range between 35% RH and 100% RH, for a temperature range of 35–100°F. Glass and Zelinka (2021) estimated that the moisture content of wood at 35, 64 °C and 65% RH would be 11.2, 11.5%. In this study, the moisture content of the hives of *Shorea* sp. was 11.22%, and the RH was 63.89%, which closely matched the above estimates and remains suitable for brood rearing.

The wood of *Shorea* sp. has hygroscopic properties suitable for hive construction. The hydroxyl groups in the wood form hydrogen bonds with water molecules (Hidayat et al. 2021), and capillary-like channels and interconnected cells facilitate moisture transfer (Sucipto et al. 2018). This characteristic helps the *Shorea* sp. wood in the hive to absorb moisture in a high moisture environment and retain water in an arid environment, keeping the relative humidity levels of the hive stable (Monder et al. 2009). Thus, hives made from *Shorea* sp. wood create an optimal microclimate that boosts the number of worker bees, improves brood development, and strengthens the colony.

The results are similar to those of Jagadeesan et al. (2022), who observed that the hive wood type has a significant impact on colony strength, brood area, and honey production of *Apis cerana indica* colonies, where hardwood hives performed better than the plywood hives. *Shorea* sp. hives were more favourable for colony development due to higher internal temperature (34.87°C) and relative humidity (63.89%) than *Dipterocarpus* sp. (temperature = 33.33 °C; RH = 58.81%) and plywood hives (temperature = 32.88 °C; RH = 56.23%) (Table 3). On the other hand, the wood moisture content was higher in the plywood hives (13.61%), and lower brood production and reduced comb coverage were related to this moisture content (Table 3). In general, these findings suggest that plywood can negatively affect bees' reproductive attempts by creating less-than-ideal microclimatic conditions and possibly by releasing harmful chemicals from recent glues. The study pinpoints that hive material is one of the important hive parameters that affects the colony performance of *A. cerana* F. in the tropics.

CONCLUSION

This research shows significant differences among several hive materials in the performance of *Apis cerana* F. and the stability of the microclimate within the hive. It is extremely important to select the correct wood properties to enhance the worker population, expand brood areas and promote colony comfort. In general, hives of *Shorea* sp. were found to provide the most favourable nesting conditions when compared with the other materials tested.

ACKNOWLEDGEMENT

This research was funded by the University of Malaysia Sabah's internal grants (GUG0443-1/2020). We thank the Sabah Rural Development Corporation (KPD) for their support during the fieldwork. Additionally, we are grateful to the Faculty of Sustainable Agriculture, UMS, for facilitating this study.

Ethical Approval
The study was conducted in accordance with the animal ethics guidelines set by the Research Management Centre, Universiti Malaysia Sabah (Reference No.: UMS/PPI1.3.2/800-1/2/3). While insects are not considered vertebrate animals under Sabah's regional animal welfare laws, all procedures involving these invertebrates strictly adhered to institutional ethical standards for animal care and research use. Additionally, all necessary precautions were taken during data collection to reduce stress and environmental impact on the honeybee colonies.

Conflicts of Interest
The authors declare no conflicts of interest.

Authors' Contributions
Conceptualisation, analysis, methodology, and writing of the original manuscript, M.I.J.J.H. and S.B.; sampling, M.I.J.J.H., B.B., and J.M.; review of the manuscript, S.B., N.C., J.A., and K.A. All authors have read and agreed to the published version of the manuscript.

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