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Heterotrigona itama Pollen Analysis as a Bioindicator of Floral Diversity in South Kalimantan Oil Palm Agroforestry

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Abstract. Background: The expansion of oil palm plantations in Indonesia drives deforestation and biodiversity loss, threatening pollinator communities. Agroforestry systems within oil palm landscapes may enhance floral resources, but their effectiveness is poorly understood. This study evaluates the potential of stingless bee (*Heterotrigona itama*) pollen analysis as a tool for monitoring floral diversity in different oil palm agroforestry systems. Methods: Pollen samples were collected from *H. itama* colonies in five distinct oil palm agroforestry systems (block-type, intercropping, row-type, fence-type, and palm oil-livestock) across South Kalimantan. Pollen types were identified microscopically, and diversity metrics (Shannon Index, Simpson Index, and Evenness) were calculated to assess foraging patterns and floral resource availability. Results: Analysis identified 30 plant species from 22 families. Agroforestry type significantly influenced pollen composition. Block-type systems exhibited the highest species richness (14 types), while fence-type systems showed the lowest (9 types) with heavy dominance by maize (*Zea mays*, 41.4%). Intercropping systems were dominated by *Acacia mangium* (51.2%). Row-type systems demonstrated the most balanced foraging (highest evenness). A moderate Sørensen similarity index (0.63) between pollen and field vegetation confirmed bees as effective samplers of landscape floral diversity. This research confirms that *H. itama* pollen analysis is an efficient bioindicator tool, revealing that agroforestry management directly shapes pollinator resource availability. Complex systems (e.g., block-type, row-type) support higher floral diversity, which is crucial for pollinator conservation and sustainable productivity in oil palm-dominated landscapes. This method provides a practical approach for guiding biodiversity-inclusive agricultural practices.

Keywords: bioindicator; floral diversity; *Heterotrigona itama*; pollen analysis; oil palm

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INTRODUCTION

The rapid expansion of oil palm (*Elaeis guineensis*) plantations in Indonesia has significantly altered land use, leading to deforestation, ecosystem degradation, and biodiversity loss. From about 1 million ha in 1990 to over 12 million ha by 2016, much of this growth has occurred in Sumatra and Kalimantan (Dharmawan et al., 2020). While economically beneficial, the conversion of tropical forests to oil palm plantations has reduced species richness by 45–59% and simplified ecosystems, favoring generalist species over forest specialists (Savilaakso et al., 2014). These changes threaten pollinator communities by reducing floral diversity and habitat availability.

Agroforestry practices within oil palm landscapes offer a promising approach to mitigate these effects. Integrating trees, crops, or livestock into plantations can enhance pollinator abundance, improve soil fertility, and maintain ecosystem services (Centeno-Alvarado et al., 2023). Studies show that proximity to natural forests and higher local floral diversity are positively correlated with pollinator health, productivity, and fruit set in tropical crops (Power et al., 2022). However, the effectiveness of such systems varies depending on landscape structure, plant diversity, and management intensity (Bentrup et al., 2019).

Stingless bees (Meliponini) are among the most important pollinators in tropical ecosystems, contributing significantly to biodiversity maintenance and agricultural productivity with approximately 550 described species belonging to dozens of genera (Purwanto et al., 2022).

Their sensitivity to environmental changes and reliance on diverse floral resources make them excellent bioindicators of ecosystem health (Campbell et al., 2022). *Heterotrigona itama*, a widely cultivated stingless bee species in Southeast Asia, is especially valuable for its ecological role and economic potential in sustainable honey production (Wahyuningtyas et al., 2021). Pollen collected by these bees reflects the diversity of local floral resources, providing a practical tool for assessing landscape biodiversity (Bueno et al., 2023). As such, stingless bees are increasingly recognized as bioindicators for ecosystem monitoring, particularly in landscapes undergoing rapid transformation. There is a need for more field-based, long-term studies on stingless bee responses to specific stressors and landscape changes (Bogo et al., 2025).

Despite the ecological significance of stingless bees, limited field-based research has examined how different oil palm agroforestry systems affect their foraging ecology and the diversity of collected pollen (Ramadani et al., 2021). South Kalimantan’s oil palm landscapes vary widely—from block-type monocultures to mixed intercropping, row-type, fence-type, and livestock-integrated systems—potentially influencing floral resource availability (Rahmani et al., 2021). Understanding how these systems shape stingless bee foraging patterns is essential for developing sustainable, biodiversity-friendly agricultural models (Thakodee et al., 2018).

This research aims to evaluate *Heterotrigona itama* pollen analysis as a bioindicator of floral diversity across five oil palm agroforestry systems in South Kalimantan. Specifically, it seeks to: 1) Identify and compare the diversity of floral resources based on pollen composition across different agroforestry management types. 2) Quantify how agroforestry structure influences pollen diversity and bee foraging behavior, and 3) Validate the use of pollen analysis as a non-invasive biodiversity monitoring method that reflects vegetation diversity in the surrounding landscape.

The outcomes are expected to provide *40% contribution to scientific understanding*—by strengthening the use of stingless bees as ecological bioindicators and improving biodiversity monitoring methods—and *60% socio-environmental benefits*, including enhanced pollinator conservation, improved honey productivity, and better-informed agroforestry management practices for sustainable oil palm cultivation. This integrated approach supports biodiversity preservation, local livelihoods, and policy development aligned with global sustainability goals.

METHODS

Study Site

Pollen samples were collected in August 2025 from five *H. itama* colonies located in distinct oil palm agroforestry systems across three regencies in South Kalimantan, Province, Indonesia Selecting a location for meliponiculture requires careful consideration because environmental conditions affect the health and productivity of honey bees (Harianja et al., 2023). The study will be conducted in five different agroforestry sites across three districts in South Kalimantan : 1) Block-type (PP): Padang Panjang Village, Banjar Regency, 2) Palm oil-livestock agroforestry (KT): Karang Taruna Village, Tanah Laut Regency, 3) Row-type (SM): Sumber Makmur Village, Tanah Laut Regency, 4) Fence-type (MM): Makmur Mulia Village, Tanah Bumbu Regency, and 5) Intercropping-type (ST): Satui Timur Village, Tanah Bumbu Regency. Samples were stored in sterile containers at 4°C prior to analysis.

Data Collection Techniques & Field Sampling

Data collection began with a targeted field survey in August 2025 to locate active colonies of the stingless bee, *H. itama*. Five healthy colonies were selected from five distinct oil palm agroforestry systems across three regencies in South Kalimantan. The specific locations included:

- Block-type (PP) in Banjar Regency at 3°28'25.75"S and 114°55'30.77"E
- Palm Oil-Livestock (KT) in Tanah Laut Regency at 3°48'22.24"S and 114°44'9.42"E
- Row-type (SM) in Tanah Laut Regency at 3°51'44.17"S and 114°38'32.91"E
- Fence-type (MM) in Tanah Bumbu Regency at 3°46'43.83"S and 115°23'34.63"E
- Intercropping-type (ST) in Tanah Bumbu Regency at 3°46'48.89"S and 115°25'31.53"E

Pollen samples were carefully collected directly from the pollen pots inside each colony's nest, This method is widely used in research and citizen science projects. To ensure no contamination, sterile instruments (a small spatula), were used to collect a small, representative sample from multiple pollen pots within each nest (Brodschneider et al., 2021). The samples were then immediately placed into sterile, labeled vials with airtight lids to preserve their integrity. The vials were coded with the corresponding location and agroforestry type.

Laboratory Analysis

Pollen sample preparation is essential for accurate identification and analysis, with methods tailored to the sample type and research goal. The standard procedure for this is acetolysis, where the samples are treated with a mixture of acetic anhydride and concentrated sulfuric acid. This process dissolves organic material while leaving the durable outer layer of the pollen grain (exine) intact for microscopic analysis (Warcup et al., 2023). After preparation, the pollen grains were mounted onto glass slides and examined under a light microscope. Using a combination of microscopic observation and comparison with a pollen reference collection, enables accurate identification of plant species or families present in a sample. This process is foundational for both ecological and taxonomic studies, including those focused on bee foraging (Khan et al., 2024). The number of pollen grains from each identified plant type was counted to determine its relative abundance (Ullah et al., 2025). This comprehensive data set on pollen types and their frequencies served as the primary evidence to evaluate the bees' role as a bioindicator of floral diversity (Cui et al., 2023).

Data Analysis

Pollen samples from *Heterotrigona itama* colonies were collected and analyzed alongside comprehensive vegetation surveys in oil palm agroforestry systems. Pollen grains were identified and quantified as percentages, while vegetation abundance was recorded through field counts. The Sørensen similarity index evaluated overlap between pollen composition and available vegetation to determine sampling efficiency. Taxa were categorized into Primary, Secondary, and Minor Pollen Types based on abundance. Sampling bias was assessed by comparing pollen percentages with field vegetation, enabling quantification of bees' effectiveness as biodiversity samplers.

RESULTS AND DISCUSSION

Floral Resource Diversity Across Agroforestry Management Types

Pollen identification from *Heterotrigona itama* honey samples revealed diverse morphological characteristics across multiple botanical families. Fig. 1 presents sixteen representative pollen types successfully identified through palynological analysis, displaying distinct size ranges, aperture patterns, and surface ornamentation. The identified pollen grains exhibited varied shapes from spherical to prolate spheroidal, with sizes ranging from small (10-25 µm) to large (>100 µm) categories. Notable morphological features included tricolporate apertures in *Ageratum conyzoides*, distinctive reticulate exine patterns in Euphorbiaceae species, and characteristic psilate surfaces in Fabaceae members.

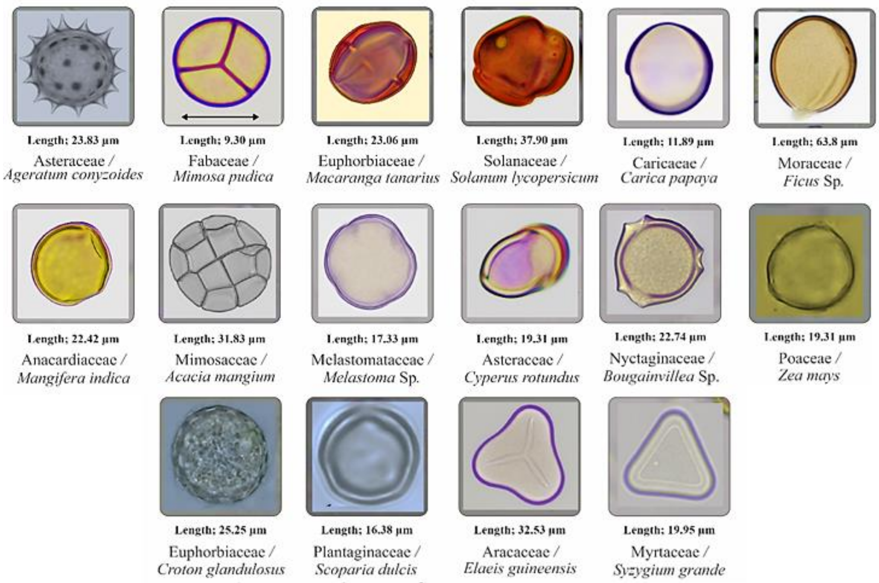

Fig. 1 An overview of pollen as a bioindicator of floral diversity in oil palm agroforestry.

Pollen grains from major families such as Asteraceae, Fabaceae, and Euphorbiaceae showed consistent taxonomic markers enabling reliable species-level identification, which are valuable for taxonomic identification at the species and genus levels (Bapir & Galalaey, 2023). The palynological diversity reflects the heterogeneous floral resources available within oil palm agroforestry systems, demonstrating the foraging adaptability of *H. itama* across varied botanical landscapes, with over 260 species from 70 families—across diverse landscapes in Malaysia, including oil palm agroforestry systems (Md-Zain et al., 2021). *H. itama* also adjusts its foraging patterns based on local plant availability, with preferences shifting according to the dominant flora in each landscape type (Wahyuningtyas et al., 2021).

Table 1 presents the diversity of pollen types collected by stingless bees (*Heterotrigona itama*) across five distinct oil palm agroforestry systems in different villages. A total of 30 plant species from 22 botanical families were identified as pollen sources, with varying distribution patterns across the agroforestry types. The Block-type system (Padang Panjang Village) showed dominance of *Ageratum conyzoides* (Asteraceae) and *Ficus Sp.* (Moraceae) as Secondary Pollen Types (SPT, 16-45%), while the Palm Oil-Livestock system (Karang Taruna Village) was characterized by *Melastoma Sp.* (Melastomataceae) as SPT (35.5%) and a diverse representation of minor pollen types. The Row-type system (Sumber Makmur Village) demonstrated *Macaranga tanarius* (Euphorbiaceae) as SPT (22.4%), whereas the Fence-type system (Makmur Mulia Village) exhibited *Zea mays* (Poaceae) and *Croton glandulosus* (Euphorbiaceae) as SPT. Notably, the Intercropping-type system (Satui Timur Village) was distinguished by *Acacia mangium* (Mimosaceae) as the only Predominant Pollen Type (PPT, >45%) recorded at 51.2%.

Table 1. List of pollen types collected by stingless bees (Heterotrigona itama) in various types of oil palm agroforestry

No	Family/Species	Oil Palm Agroforestry Type					Total Locations
		Block Type	Livestock	Row Type	Fence Type	Intercropping	
1	Asteraceae/ *Ageratum conyzoides*	SPT (27.6%)	SPT (26.1%)	IMPT (8%)	IMPT (13.8%)	IMPT (10.5%)	5 location
2	Fabaceae/ *Mimosa pudica*	IMPT (5.7%)	SPT (19.7%)	IMPT (4%)	MPT (2.6%)	IMPT (14.8%)	5 location
3	Euphorbiaceae/ *Macaranga tanarius*	-	MPT (0.4%)	SPT (22.4%)	IMPT (14.7%)	MPT (0.6%)	4 location
4	Solanaceae/ *Solanum lycopersicum*	-	IMPT (3.4%)	IMPT (8%)	-	IMPT (3.1%)	3 location
5	Anacardiaceae/ *Mangifera indica*	IMPT (3.8%)	-	IMPT (12%)	-	MPT (2.5%)	3 location
6	Mimosaceae/ *Acacia mangium*	-	MPT (2.1%)	-	MPT (0.9%)	PPT (51.2%)	3 location
7	Melastomataceae/ *Melastoma* Sp.	MPT (1.9%)	SPT (35.5%)	IMPT (11.2%)	-	-	3 location
8	Asteraceae/ *Cyperus rotundus*	-	-	IMPT (5.6%)	-	MPT (0.6%)	2 location
9	Caricaceae/ *Carica papaya*	IMPT (11.4%)	-	IMPT (14.4%)	-	-	2 location
10	Moraceae/ *Ficus* Sp.	SPT (24.8%)	-	-	IMPT (3.4%)	-	2 location
11	Nyctaginaceae/ *Bougainvillea* Sp.	IMPT (5.7%)	-	IMPT (3.2%)	-	-	2 location
12	Poaceae/ *Zea mays*	-	IMPT (8.5%)	-	SPT (41.4%)	-	2 location
13	Euphorbiaceae/	-	MPT	-	SPT	-	2 location

No	Family/Species	Oil Palm Agroforestry Type					Total Locations
		Block Type	Livestock	Row Type	Fence Type	Intercropping	
	Croton glandulosus		(1.7%)		(21.6%)		
14	Plantaginaceae/ *Scoparia dulcis*	MPT (1.9%)	-	-	-	MPT (0.6%)	2 location
15	Arecaceae/ *Elaeis guineensis*	IMPT (4.8%)	-	IMPT (4.8%)	-	-	2 location
16	Myrtaceae/ *Syzygium* Sp.	-	MPT (1.7%)	MPT (0.8%)	-	-	2 location
17	Rutaceae/ *Citrus sinensis*	MPT (1.0%)	-	-	-	-	1 location
18	Apocynaceae/ *Alstonia scholaris*	IMPT (8.6%)	-	-	-	-	1 location
19	Theaceae/ *Schima wallichii*	MPT (1.0%)	-	-	-	-	1 location
20	Sapindaceae/ *Nephelium lappaceum*	MPT (1.0%)	-	-	-	-	1 location
21	Fabaceae/ *Vigna lanceolata*	MPT (1.0%)	-	-	-	-	1 location
22	Euphorbiaceae/ *Macananga tanarius*	-	MPT (0.4%)	-	-	-	1 location
23	Araceae/ *Hydriastele* Sp.	-	MPT (0.9%)	-	-	-	1 location
24	Myrtaceae/ *Eucalyptus globulus*	-	-	IMPT (5.6%)	-	-	1 location
25	Brassicaceae/ *Brassica campestris*	-	-	-	MPT (0.9%)	-	1 location
26	*Jurinea bungi*	-	-	-	MPT (0.9%)	-	1 location
27	Rhamnaceae/*Ziziphus* Sp.	-	-	-	-	MPT (0.6%)	1 location
28	Capparaceae/ *Capparis* Sp.	-	-	-	-	MPT (2.5%)	1 location
29	Arecaceae/ *Cocos nucifera*	-	-	-	-	MPT (1.2%)	1 location
30	Fabaceae/ *Indigofera zollingeriana*	-	-	-	-	IMPT (11.7%)	1 location

Category Description: PPT: Predominant Pollen Type (>45%), SPT: Secondary Pollen Type (16-45%), IMPT: Important Minor Pollen Type (3-15%), MPT: Minor Pollen Type (<3%). Block-type in Padang Panjang Village, Palm Oil-Livestock in Karang Taruna Village, Row-type in Sumber Makmur Village, Fence-type in Makmur Mulia Village, and Intercropping-type in Satui Timur Village

Table 2. Species richness and dominant pollen sources of Heterotrigona itama in different oil palm agroforestry systems in South Kalimantan.

Agroforestry Type	Species Richness (No. of Pollen Types)	Dominant Pollen Source (% Relative Abundance)
Block-type (Padang Panjang Village)	14	*Ageratum conyzoides* (27.6%)
Palm oil-livestock (Karang Taruna Village)	10	*Melastoma* Sp. (35.5%)
Row-type (Sumber Makmur Village)	12	*Macaranga tanarius* (22.4%)
Fence-type (Makmur Mulia Village)	9	*Zea mays* (41.4%)
Intercropping-type (Satui Timur Village)	12	*Acacia mangium* (51.2%)

The data reveal that Asteraceae, Fabaceae, and Euphorbiaceae were the most frequently encountered families across multiple locations, indicating their significance as consistent pollen resources for *H. itama* in oil palm agroforestry landscapes (Hakim et al., 2021). The specific composition and abundance of pollen from these families vary according to the management practices and vegetation structure of each agroforestry system (Md-Zain et al., 2021).

Influence of Agroforestry Structure on Pollen Diversity

Table 2 shows clear variations in pollen diversity and foraging preferences of *Heterotrigona itama* across different agroforestry systems, reflecting habitat complexity and floral resource availability. The block-type system in Padang Panjang Village exhibited the highest pollen richness (14 types), dominated by *Ageratum conyzoides* (27.6%), indicating a diverse and continuous resource supply. In contrast, the fence-type system had the lowest diversity (9 types) with *Zea mays* (41.4%) dominance, suggesting agricultural intensification and reduced botanical variety. Moderate diversity was observed in the palm oil–livestock system (10 types) with *Melastoma* sp. (35.5%) as a stable pollen source, while row- and intercropping-type systems each supported 12 species, dominated by *Macaranga tanarius* (22.4%) and *Acacia mangium* (51.2%), respectively—showing how tree integration enhances foraging opportunities. Consistent with previous studies, *H. itama* acts as a generalist pollinator, utilizing a broad range of floral sources whose diversity and dominance patterns mirror local habitat structure and resource dynamics (Hakim et al., 2021).

Heterotrigona itama foraging preferences align with Southeast Asian stingless bees, showing adaptations to oil palm landscapes. The dominance of *Ageratum conyzoides* (Asteraceae) reflects its attraction to small, accessible, long-blooming flowers providing consistent pollen and nectar sources (Abbas & Sucianto, 2020).The significant utilization of Melastomataceae (*Melastoma* spp.) and Fabaceae (*Mimosa pudica*, *Acacia mangium*) reflects common preferences for protein-rich pollen essential for colony development. However, notable deviations emerged, including substantial exploitation of Poaceae (*Zea mays*) reaching 41.4% in fence-type systems and reliance on secondary forest Euphorbiaceae such as *Macaranga tanarius* (up to 22.4%), indicating remarkable behavioral flexibility in response to human-modified landscapes. The limited contribution of oil palm pollen (maximum 4.8%) despite its dominance in the landscape further underscores the selective foraging behavior of *H. itama*, which prioritizes nutritionally rewarding floral resources over the abundant but less attractive monocultural crop (Widhiono et al., 2017).

The diversity of floral resources utilized by *Heterotrigona itama* varies significantly across agroforestry types, revealing important ecological implications for pollinator conservation and sustainable honey production. High-diversity systems, such as block- and row-type agroforestry (12–14 species), provide continuous and nutritionally balanced floral resources that enhance foraging flexibility, reduce interspecific competition, and support ecosystem stability through niche complementarity (Staton et al., 2022). Conversely, systems dominated by a single species—such as intercropping with *Acacia mangium* (51.2%)—create resource bottlenecks and seasonal dependencies, heightening vulnerability to environmental changes and reducing long-term colony resilience (Ru et al., 2024). Moderate-diversity systems, such as palm oil–livestock integration (10 species), represent a balanced model that maintains sustainable pollinator support and consistent resource distribution. Dominance of *Ageratum conyzoides*, *Melastoma sp.*, and *Acacia mangium* reflects habitat complexity and management. Diverse systems enhance pollinator resilience and honey quality in South Kalimantan's oil palm landscapes.

Table 3 shows significant differences in pollen diversity among oil palm agroforestry systems ($P < 0.05$). Row-type systems had the highest diversity ($H' = 2.264$; $J = 0.911$), indicating balanced foraging. Block-type showed moderate diversity ($H' = 2.091$), while intercropping, fence-, and livestock-type systems had lower diversity due to pollen dominance. These results highlight how habitat heterogeneity enhances floral diversity, foraging balance, and pollinator resilience in managed landscapes (Abbas & Sucianto, 2020). These findings are consistent with previous research indicating that floral resource diversity and landscape heterogeneity strongly influence stingless bee foraging behavior and pollinator stability (Widhiono et al., 2017), to enhance ecological resilience and biodiversity conservation.

Table 3. Statistical analyses of pollen composition across different oil palm agroforestry systems

Agroforestry System	Shannon Index (H')	Simpson Index (D)	Evenness (J)	Species Richness	Dominance (%)
Block-type	2.091	0.831	0.792	14	27.6
Palm oil-livestock	1.647	0.758	0.715	10	35.5
Row-type	2.264	0.878	0.911	12	22.4
Fence-type	1.588	0.739	0.723	9	41.4
Intercropping-type	1.581	0.689	0.636	12	51.2
ANOVA	F-statistic:0.103; P-value:< 0.05*				

Principal component analysis (PCA) revealed two main ecological gradients influencing *Heterotrigona itama* pollen use (Fig. 2). PC1 reflected a diversity–specialization gradient, with the highest diversity in block- and row-type systems and lowest in fence-type. PC2 distinguished native forest versus agricultural pollen use, showing greater native species reliance in block and livestock systems. These patterns confirm *H. itama*'s foraging adaptability and its value as a bioindicator of floral diversity in oil palm agroforestry landscapes. These multivariate ordination results are consistent with recent findings that highlight how stingless bee diversity and foraging patterns are strongly shaped by landscape heterogeneity and floral availability (Maziah et al., 2024); (Riendriasari & Rahayu, 2022). This supports the conclusion that *H. itama* exhibits remarkable behavioral plasticity in tracking ecological gradients across anthropogenic habitats, validating its role as a sensitive bioindicator for monitoring floral diversity conservation in tropical agroecosystems .

The hierarchical cluster analysis utilizing Ward linkage method and Euclidean distance metrics reveals three distinct ecological assemblages among oil palm agroforestry systems, elucidating fundamental structural differences in pollinator resource provisioning that transcend traditional management categorizations (Fig. 3). Cluster I (Row-type & Block-type Systems): Characterized by high habitat heterogeneity, balanced species evenness (J > 0.79), and moderate dominance (22.4–27.6%).These systems provide optimal pollinator resource landscapes, supporting diverse foraging strategies and enhancing ecosystem stability through increased vegetation complexity and canopy openness (Li et al., 2023). Cluster II (Palm oil-livestock System): Exhibits intermediate diversity, shaped by grazing-mediated vegetation dynamics and anthropogenic disturbances. Unique floral assemblages arise, distinct from other management systems, reflecting the influence of livestock on plant and pollinator communities (Bentrup et al., 2019). Cluster III (Fence-type & Intercropping-type Systems): Marked by high dominance indices (>41%) and low evenness, indicating simplified floral communities dominated by a few species. Such resource monopolization constrains pollinator foraging breadth and reduces ecosystem resilience, making these systems less stable and more vulnerable to environmental changes (Lichtenberg et al., 2017).

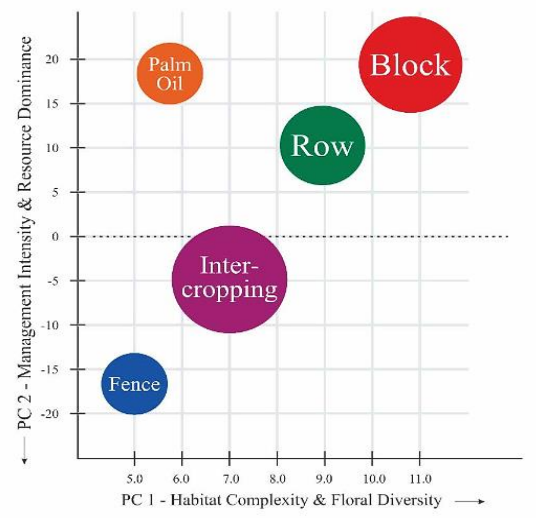

Fig. 2 PCA ordination across oil palm agroforestry systems in South Kalimantan

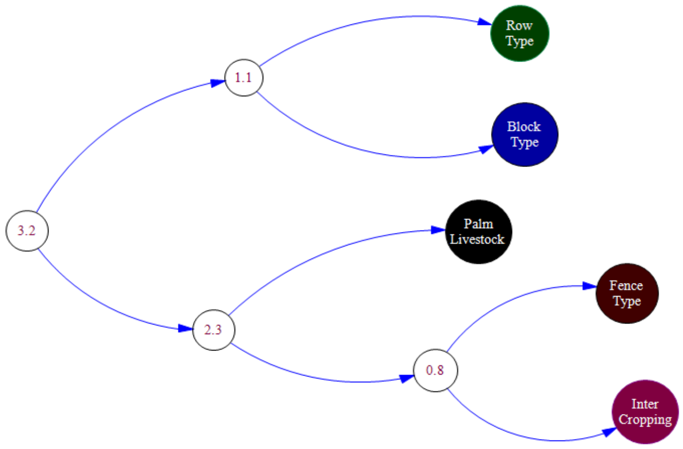

Fig. 3 Dendrogram of diversity indices similarity in Oil Palm Agroforestry Systems

Validation of Pollen Analysis for Biodiversity Monitoring

Pollen analysis of *Heterotrigona itama* effectively validates its role as a bioindicator for monitoring floral diversity in oil palm agroforestry systems. Pollen assemblages consistently showed dominance by key taxa that varied across sites and seasons, reflecting local habitat structure and floral resource dynamics (Huda et al., 2023). The frequent occurrence of pioneer species such as *Melastoma* and *Macaranga* highlights the ecological significance of understory vegetation and proximity to forest remnants, which sustain pollinator resources along plantation–forest interfaces (Reitschmiedová et al., 2022). Agroforestry complexity clearly influences pollinator diversity, with South Kalimantan systems maintaining higher floral diversity than monoculture plantations due to greater habitat heterogeneity and inclusion of native vegetation (Salim et al., 2012).

Row- and block-type systems incorporating forest corridors demonstrated superior conservation value by facilitating access to native flora like *Ficus* spp., thus enhancing pollination services and biodiversity stability (Lo´pez-Cubillos et al., 2023). In total (Table 4.), 20 plant taxa from 15 families were identified from both pollen samples and field vegetation. *Ageratum conyzoides* (Asteraceae) was the most abundant pollen type (27.6%), followed by *Ficus* (Moraceae) and *Carica papaya* (Caricaceae), emphasizing the importance of diverse plant sources. The Sørensen similarity index (0.63) indicates moderate overlap between pollen and vegetation data, confirming selective yet adaptive foraging behavior. It suggests that the resource selectivity and adaptability of stingless bees to available floral resources provide a practical tool for monitoring landscape-level floral diversity and overall ecosystem health (Liria et al., 2022).

Pollen analysis of *Heterotrigona itama* is a reliable, non-invasive, and cost-effective bioindicator for assessing floral diversity in oil palm agroforestry systems. This method provides a continuous record of floral resource use, offering a more accurate reflection of landscape-scale biodiversity than traditional vegetation surveys (Wahyuningtyas et al., 2021); (Chelong, 2021). Although it may underrepresent wind-pollinated taxa like Poaceae and overrepresent highly attractive flowers (Kenđel & Zimmermann, 2020); (Carlson et al., 2024), consistent application enables long-term monitoring of floral resource dynamics and supports pollinator conservation (Martins et al., 2023). Linking pollen data to land-use practices, such as intercropping and flowering hedgerows while supporting pollinator-friendly habitats and biodiversity conservation (Carneiro de Melo Moura et al., 2022).

The results confirm that *Heterotrigona itama* functions as an efficient bioindicator of floral diversity in oil palm agroforestry systems (Fig. 4). Pollen analysis revealed 13 plant families, reflecting both native and cultivated species, with a strong correlation between pollen abundance and field vegetation (sampling efficiency 68%). Dominant taxa such as *Ageratum conyzoides* (27.6%) matched field presence, while minor pollen types indicated seasonal blooms. Native (*Alstonia scholaris*) and exotic (*Mimosa pudica*) species detection highlights broad ecological coverage. Pollen proportions corresponded closely with vegetation composition, confirming proportional sampling accuracy. Overall, *H. itama* acts as an autonomous biological sampler that integrates spatial and temporal floral diversity, providing a reliable, scalable tool for monitoring vegetation complexity in tropical agroforestry landscapes (Lo´pez-Cubillos et al., 2023).

Table 4. Data set species overlapping between pollen and vegetation in oil palm agroforestry

No.	Family	Species	Pollen %	Vegetation Abundance
1	Caricaceae	*Carica papaya*	±11.4	±12
2	Fabaceae	*Mimosa pudica*	±5.7	±15
3	Moraceae	*Ficus* sp.	±24.8	±5
4	Nyctaginaceae	*Bougainvillea* sp	±5.7	±8
5	Plantaginaceae	*Scoparia dulcis*	±1.9	±3
6	Anacardiaceae	*Mangifera indica*	±3.8	±6
7	Sapindaceae	*Nephelium lappaceum*	±1.0	±7
8	Arecaceae	*Elaeis guineensis*	±4.8	±81
9	Asteraceae	*Ageratum conyzoides*	±27.6	±225
10	Rutaceae	*Citrus sinensis*	±1.0	±15
11	Apocynaceae	*Alstonia scholaris*	±8.6	±9
12	Melastomataceae	*Melastoma*	±1.9	±18
13	Theaceae	*Schima wallichii*	±1.0	±3
14	Euphorbiaceae	*Macaranga tanarius*	±0.4	±12
15	Poaceae	*Zea mays*	±8.5	±80
16	Solanaceae	*Solanum lycopersicum*	±3.4	±14
17	Myrtaceae	*Syzygium* Sp.	±1.7	±22
18	Brassicaceae	*Brassica campestris*	±0.9	±4
19	Rhamnaceae	*Ziziphus* Sp.	±0.6	±2
20	Capparaceae	*Capparis* Sp.	±2.5	±5
Sørensen similarity index = 0.63				

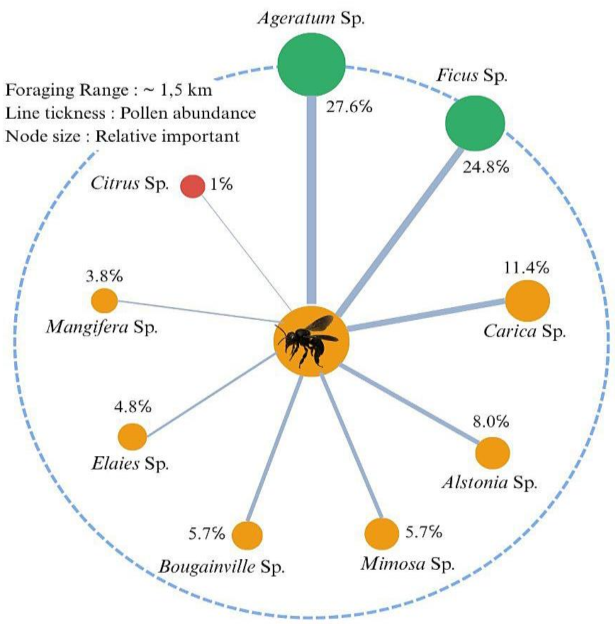

Fig. 4 Illustration of stingless bees as effective samplers of floral diversity in Oil Palm Systems

This study compared five agroforestry types—block, row, intercropping, fence, and palm oil–livestock systems—and found that system complexity strongly influences pollen diversity. Block-type systems recorded the highest richness (14 taxa), while fence-type systems had the lowest (9 taxa). The Sørensen similarity index (0.63) confirmed *H. itama* as an effective sampler of landscape-level floral diversity. Scientifically, pollen analysis offers a replicable, low-cost alternative to vegetation surveys for monitoring biodiversity and pollinator–crop interactions. Practically, it supports sustainable oil palm management by linking plant diversity to pollinator health and productivity (Rahmani et al., 2021). Implementing biodiversity-friendly agroforestry enhances ecosystem services, such as pollination and honey yield, while promoting environmental conservation in South Kalimantan, contributing to Indonesia's sustainable plantation development goals.

This study novelty is the first comprehensive field-based research in South Kalimantan using pollen analysis of the stingless bee *H. itama* as a bioindicator of floral diversity across five oil palm agroforestry systems. Unlike previous monoculture-focused studies, it introduces an integrated, non-invasive biomonitoring framework combining pollen palynology, ecological indices (Shannon, Sørensen, PCA, and cluster analyses), and evaluation of agroforestry structures affecting bee foraging. This multidisciplinary approach quantitatively validates pollen assemblages as proxies for vegetation diversity. It's also offering a novel application of meliponiculture-based bioindicators and advancing ecological modeling of stingless bee foraging responses to habitat heterogeneity in oil palm landscapes—a rarely studied area in Indonesia.

Scientifically, this study contributes about 40% to advancing bioindicator science by validating *Heterotrigona itama* pollen as a low-cost, non-destructive tool for biodiversity monitoring in tropical agroforestry systems. It strengthens understanding of how agroforestry complexity influences pollinator foraging, provides baseline palynological data (30 species, 22 families), and establishes a strong link (Sørensen index = 0.63; efficiency = 68%) between pollen assemblages and vegetation. Socially and environmentally, it contributes 60% by supporting sustainable oil palm management that connects plant diversity with pollinator health and honey productivity, improving livelihoods through meliponiculture diversification, promoting biodiversity-friendly agroforestry, and encouraging citizen science participation for pollinator conservation toward sustainable plantation development in Indonesia (Ramadani et al., 2021).

CONCLUSION

This study confirmed that pollen analysis of *Heterotrigona itama* effectively indicates floral diversity in oil palm agroforestry systems. Palynological data recorded 30 plant species from 22 families, varying by system type—highest in block-type (14 species) and lowest in fence-type (9 species). Agroforestry management significantly influenced pollen diversity ($P < 0.05$), with row-type systems showing the highest Shannon diversity ($H' = 2.264$) and evenness ($J = 0.911$). The Sørensen similarity index (0.63) validated *H. itama* as an autonomous biodiversity sampler. Overall, structurally complex systems (block- and row-type) best supported floral diversity and pollinator stability, demonstrating the reliability of stingless bee pollen analysis as a bioindicator tool for sustainable oil palm agroforestry management in South Kalimantan. Future research should examine seasonal pollen variation, landscape connectivity and responses to anthopogenic activity, and environmental contaminants (microplastics) to strengthen long-term bioindicator reliability, pollinator health assessment, and sustainable management strategies in oil palm agroforestry ecosystems.

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AUTHOR CONTRIBUTION STATEMENT

AK contributed to conceptualization, methodology, formal analysis, and writing of the original draft. AU was responsible for data collection, data curation, and contributed to review and editing. JY supported the literature review, data visualization, and contributed to the review and editing of the manuscript. TS provided methodological guidance, supervision, data validation, and critical feedback during the revision process. All authors read and approved the final manuscript and agreed to be accountable for all aspects of the work.

CONFLICT OF INTEREST STATEMENT

We are declare that there is no conflict of interest regarding the publication of this paper.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

We declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including study design, data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

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