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# Pollen foraging preference based on floral resource distance in *Tetragonula biroi*

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**Abstract.** *Nuraeni S, Tiwi AA, Prastiyo A. 2025. Pollen foraging preference based on floral resource distance in* Tetragonula biroi. *Asian J Agric 9: 423-432.* The stingless bee *Tetragonula biroi* plays a vital role as a pollinator and depends primarily on pollen and nectar for nutrition. Understanding its foraging behavior is essential for optimizing floral resource management in meliponiculture systems. This study investigates the foraging preferences of *T. biroi* based on the distance of floral resources in Awani Bee Garden, Makassar, South Sulawesi, Indonesia. Pollen identification was conducted using light microscopy on bee bread samples collected from three hives, and the spatial distribution of flowering plants around the hives was documented. This research was conducted from November 2023 to February 2025, using descriptive analysis of pollen types and plant distance from the hive. A Spearman's correlation analysis was also conducted to examine the relationship between the distance of floral sources and the percentage of pollen collected. Foraging preference was operationally defined as the percentage of pollen collected from each plant species relative to its distance from the hive. Results revealed that *T. biroi* collected pollen from 18 plant species located at distances ranging from 2 to 498 m. The most dominant pollen sources were *Clerodendrum paniculatum* (16.87%), *Macaranga tanarius* (15.20%), and *Carica papaya* (13.97%). Over 70% of the total pollen came from plant species located within 10 m of the hive, such as *Capsicum annuum* (2 m, 6.93%), *Mangifera indica* (2 m, 7.49%). However, the bees also utilized distant sources such as *Turnera subulata* (485 m, 0.56%) and *Antigonon leptopus* (498 m, 2.12%), demonstrating flexible foraging behavior within their ecological range. Spearman's correlation showed a weak negative relationship between plant distance and pollen percentage ($\rho = -0.387$) with $p>0.05$, indicating that the preference for nearby floral sources was not statistically significant but ecologically observable. These findings suggest that while proximity plays a role in foraging, *T. biroi* exhibits adaptable behavior based on resource distribution.

**Keywords:** Floral diversity, foraging, habitat, pollination, stingless bee

## INTRODUCTION

Previous studies have shown that distance plays a role in the foraging preferences of stingless bees, including species in the genus *Tetragonula*. These bees tend to collect pollen and nectar from floral sources located closer to their nests (Gresty et al. 2018). Villanueva-Gutiérrez et al. (2015) and Hrncir et al. (2019) reported that stingless bees primarily utilize nearby flowers and only expand their foraging range when local floral resources are scarce or competition is high. *Tetragonula biroi* can forage at distances of up to 500 m in natural conditions, especially when nearby floral resources are limited (Prastiyo et al. 2024). Wayo et al. (2020) further highlighted the evolutionary flexibility of stingless bees in adapting their foraging behavior across tropical landscapes. Recent research also emphasizes that foraging strategies in stingless bees are influenced by many factors, including flower accessibility, landscape heterogeneity, and colony needs (Pereira et al. 2025). These findings suggest that distance to floral sources should be considered a key ecological variable in understanding and managing the foraging behavior of stingless bees.

Foraging behavior in the stingless bee is shaped by a combination of floral species diversity and resource accessibility (Machado et al. 2020). Plants that are close to the nest are usually favored due to the reduced energy cost of travel, particularly when they offer abundant and high-quality pollen (Fowler et al. 2016). Nonetheless, bees still travel greater distances when high-reward resources are scarce nearby, indicating a flexible but strategic approach to foraging. This behavior underscores the importance of floral proximity, not just in terms of pollination efficiency but also in the nutritional composition of collected pollen. Understanding the rule of spatial configuration in foraging decision making is essential for planning landscape features in meliponiculture settings and guiding the placement of forage plants around apiaries.

Beyond proximity and richness, the temporal availability of floral resources plays a pivotal role in shaping pollen selection. Seasonal shifts in flowering phenology influence which plants are accessible during specific months, compelling bees to alter foraging routes and diets over time (Breda et al. 2024). Interspecific competition among stingless bee can intensify selective pressures, as colonies must adjust to floral abundance and competing pollinators (Roubik et al. 2023). Local land-use changes, such as agricultural expansion and deforestation, further restrict access, reducing floral heterogeneity and narrowing the nutritional spectrum of bee bread (Newman et al. 2021). Microscopic palynology, the practice of identifying pollen types preserved in bee bread, provides a robust method for analyzing foraging behavior. Techniques such as safranin and glycerin staining allow for the examination of morphological characteristics like pollen size, shape, and aperture structure, enhancing taxonomic identification (Jayadi and Susandarini 2021). The Awani Bee Garden in South Sulawesi hosts a diverse range of floral species that serve as key pollen sources for stingless bees. The distance between these plants and the beehives creates a natural experimental setting to explore how spatial factors influence pollen collection in *T. biroi* colonies.

This study offers new insight into the foraging ecology of *T. biroi* by investigating how the distance of floral resources from the hive affects pollen selection. While earlier studies have emphasized floral richness and nutritional value, this research highlights spatial proximity as a key determinant of foraging strategies, linking energetic efficiency to the diversity of collected pollen. Using microscopic palynology and field data from the Awani Bee Garden, we demonstrate how floral distance influences bee bread composition, thereby providing evidence-based recommendations for enhancing forage arrangements in meliponiculture. The findings underscore that diverse pollen intake enhances colony resilience to environmental stress and seasonal fluctuations (Mohammad et al. 2021). *Tetragonula* species adjust their foraging ranges based on landscape structure and seasonal floral dynamics, thereby efficiently exploiting both nearby and distant plant resources (Prado et al. 2021; Roubik 2023). This study aims to examine the influence of floral resource distance on the pollen foraging behavior of *T. biroi*. The hypothesis of this research is that *T. biroi* preferentially collects pollen from nearby floral sources, reflecting spatially adaptive foraging behavior.

## MATERIALS AND METHODS

### Research study

This research was conducted from November 2023 to February 2025 at the Awani Bee Garden in Makassar, South Sulawesi, Indonesia. This stingless bee education park is located within the urban forest area on the Universitas Hasanuddin, Indonesia, and is dedicated to the introduction and conservation of various stingless bee species, including *Tetragonula biroi* and *Tetragonula laeviceps*. Geographically, the site is positioned at an elevation of 17 m above sea level, with coordinates 5°07'48.43"S 119°29'00.93"E (Figure 1).

A total of three colonies were used in this study, consisting of 29 colonies. All colonies were housed in standard wooden box hives of the same dimensions and design. The hives were mounted on wooden stands arranged in parallel rows, with each colony spaced 2-3 m apart to reduce interspecific interference and to facilitate access. The colonies were arranged in individual meliponaries but housed in the same open structure and exposed to direct sunlight and heavy rain. The colonies had been established at the site since 2021 before the start of pollen collection to ensure acclimatization and foraging stability. No additional food was provided during the data collection period to ensure that pollen samples accurately reflected natural foraging behavior. The surrounding environment is characterized by a tropical monsoon climate with an average annual temperature of around 27-30°C and relative humidity ranging from 65-85%. Vegetation around the meliponaries includes a mixture of flowering shrubs, fruit trees such as *Mangifera indica*, and introduced species such as *Calliandra* sp., all of which contribute as potential floral resources for bees.

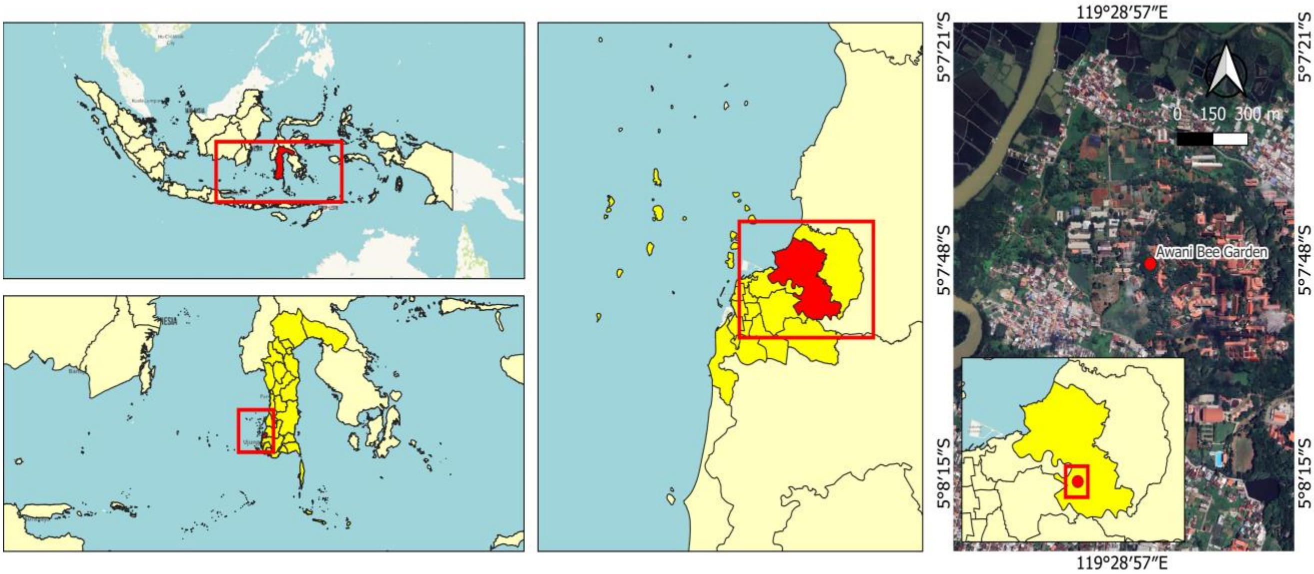

**Figure 1.** Map of research location at Awani Bee Garden, Makassar, South Sulawesi, Indonesia

### Pollen collection and observation on bee bread

Observation of pollen types in bee bread was conducted using three colonies of *T. biroi* at the Awani Bee Garden, South Sulawesi, Indonesia. Samples were collected under clear and hot weather conditions, avoiding rainy or excessively humid days to ensure foraging activity was not disrupted. Sampling was performed once a week over a three-week period, resulting in three total sampling events per colony. From each colony, 10 g of bee bread were soaked in 70% alcohol, and 4 g were then homogenized with 2 mL of 70% alcohol, 1 mL of glycerin, and 1 mL of safranin. Small portions of the mixture were placed on 15 microscope slides per colony (totaling 45 slides) using tweezers. Wax was applied to the edges of each slide and gently heated before being sealed with a cover slip. This study did not involve an experimental plot layout; instead, the distance between each identified flowering plant and the hive was measured directly in the field using a measuring tape and GPS, following the identification of pollen types under a light microscope.

### Observation of pollen in flowers

To identify the floral pollen sources available to stingless bees, sampling was conducted once during the local flowering season, covering all flowering plants within a 500-m radius of the meliponiculture area. Both herbaceous plants and flowering trees were included in the survey, while non-flowering plant species were also recorded and taxonomically identified. Pollen was directly collected from the anthers of blooming flowers between 07:00 and 09:00 under clear and dry weather conditions to ensure optimal pollen viability. Each collected pollen sample was placed into a tube containing 1 mL of distilled water and centrifuged for 10 minutes. The supernatant was discarded, and 10 mL of sulfuric acid ($H_2SO_4$) was added, followed by another centrifugation step. After discarding the acid, the pellet was rinsed sequentially with 1 mL of distilled water and 1 mL of glacial acetic acid ($CH_3COOH$), each followed by centrifugation and removal of the liquid. The final pellet was mixed with 1 mL of glycerin and 1 mL of safranin, then homogenized. A small amount of this stained pollen suspension was mounted on a microscope slide using tweezers and sealed with melted wax under a cover slip (Nuraeni et al. 2024). Microscopic observations were carried out at 400× magnification using a binocular microscope (Zortéa et al. 2022). The reference pollen slide collection generated from these field-identified flowers was later used as a comparative basis for identifying pollen types found in bee bread. The identification of pollen was carried out by examining its morphological features, including the type of pollen, the shapes observed from both polar and equatorial views, and the surface patterns of the exine layer (Paul and Chowdhury 2020).

### Pollen observation on bee bread

Fifteen microscope slides were prepared for each colony and examined under a binocular microscope at 400× magnification to identify the types of pollen present in the bee bread. Identification was based on morphological criteria including grain size, shape, aperture type, and surface ornamentation, which are commonly used in melissopalynology. The pollen grains observed were compared with those obtained from floral samples collected around the study site to support accurate identification. To support spatial analysis, the layout of flowering plants was documented within four concentric distance zones (0-10 m, 11-50 m, 51-250 m, and >250 m), and each plant species within those zones was mapped and coded. To enhance the clarity of structural features essential for pollen recognition, especially for tropical plant taxa, the samples were treated using an acetolysis technique as described by Erdtman (1953). Pollen grains in each subsample were then counted and analyzed to reflect the composition of floral sources visited by bees before collection (Louveaux et al. 1978; Raffiudin et al. 2024). Pollen identification was verified using reference collections of pollen and spores from Universitas Hasanuddin Herbarium, supplemented by digital images from the Australasian Pollen and Spore Atlas (http://apsa.anu.edu.au).

### Measuring the distance of the pollen source from the bee hive

The distance from the hive, the beehive, to the pollen source was mesured using a Garmin 64S GPS unit. Measurements were taken from the hive to the nearest source of floral pollen.

### Observation of forages and flowering

The identification of plant species that potentially provide pollen, nectar, and resin was carried out through direct field observation, following the method of Agussalim et al. (2017). For each flowering species observed, one or two flower samples were taken for examination. Petals were gently removed to assess the presence of nectar, which was indicated by sweet, watery secretions at the base of the flower. Pollen availability was determined by inspecting the anthers for visible yellow or powder-like grains. Although bee activity was not directly observed for resin collection, certain plant species known from literature to produce resinous secretion, such as from buds, young stems, or bark, were noted as potential resin sources. To establish the relationship between plant species and the resources actually collected by bees, pollen grains collected from flowers were prepared on reference microscope slides. These slides were then used for comparative identification with pollen grains found in bee bread samples collected from the colonies. This matching process to confirm which plant species contributed pollen to the diet of *T. biroi* during the study period. Floral phenology data were recorded monthly from January to December 2024 to track flowering patterns and resource availability.

### Data analysis

Data was analyzed descriptively. In addition, Spearman's correlation analysis was performed to examine the relationship between the distance of floral sources and the proportion of each pollen type found in the bee bread. This test assessed whether the proximity of flowering plants influenced the frequency of pollen collected by *T. biroi*. The percentage of each pollen type in the bee bread was calculated, and the distance from the hive to each pollen source was recorded. The percentage of pollen from each plant species in the bee bread was calculated using the following formula:

$$X = \Sigma A / \Sigma B \times 100\%$$

Where X is the percentage of the number of types of pollen of one type of plant in bee bread (%), A is the number of pollen of one type of plant (grain), and B is the number of all pollen observed from all types of plants in one preparation (grain).

## RESULTS AND DISCUSSION

### Plant diversity represented in the pollen of *Tetragonula biroi* bees

A total of 18 plant species were identified as pollen sources. The results of the percentage of plant pollen (Figure 2) found in *Tetragonula biroi* bees in Awani Bee Garden, the highest was in the *Clerodendrum paniculatum* plant (16.87%), followed by *Macaranga tanarius* (15.20%), and *Carica papaya* (13.97%). Plants with the lowest percentage were *Turnera subulata*, *Plumeria alba*, and *Tectona grandis*, with 1% each. These results indicate that *T. biroi* prefers certain plants as a pollen source, which is related to the availability and ease of flower access. The diversity of pollen sources also reflects the abundance of vegetation around the cultivation location that supports the nutritional needs of the bee colony.

The pollen foraging preference exhibited by *T. biroi* demonstrates a strong correlation between the selection of flowering plants and both floral morphological traits and the abundance of available pollen resources. Plant species such as *C. paniculatum*, *M. tanarius*, and *C. papaya* dominate the pollen composition in bee bread, serving as key sources of protein and energy essential for colony survival (Rahmad et al. 2024). The predominance of pollen from these species supports the conclusion that *T. biroi* tends to favor flowers with morphological characteristics that facilitate efficient foraging. Moreover, the accessibility of cultivated plants such as *C. papaya* indicates that commonly found species in home gardens and agro-ecosystems can act as supplemental or alternative resources when natural vegetation is limited (Pushpakumara et al. 2020).

The diversity and spatial distribution of flowering plants in the landscape surrounding the nest play a crucial role in shaping foraging patterns and influencing the bees' reliance on local floral resources (Pardee et al. 2023). The presence of species with low pollen representation, such as *T. subulata* and *P. alba*, likely reflects constraints such as short blooming periods, low population densities, or lower attractiveness to foraging workers. Stingless bees, including *T. biroi*, are highly dependent on the continuous availability of pollen sources throughout the day (Maia-Silva et al. 2020), highlighting the ecological importance of plant species that flower year-round. For instance, *H. rosa-sinensis* contributes to maintaining colony nutritional stability due to its consistent pollen production (Zhou et al. 2023).

Urban forests, which offer both seasonal and perennial flowering plants, support pollen diversity while promoting floral constancy and visual learning in bees (Schulze-Albuquerque et al. 2020). The ability of stingless bees to discriminate floral resources is strongly influenced by their visual and olfactory systems, which are able to recognize floral colors and scents during foraging flights (Koethe et al. 2020). Recent research has also revealed that bees can detect certain floral volatiles (VOCs), improving their orientation towards beneficial plant species even in patchy landscapes (Conchou et al. 2019; Giuliani et al. 2020). Therefore, enhancing floral diversity within the urban forest landscape represents a strategic effort to support the sustainability of *T. biroi* colonies.

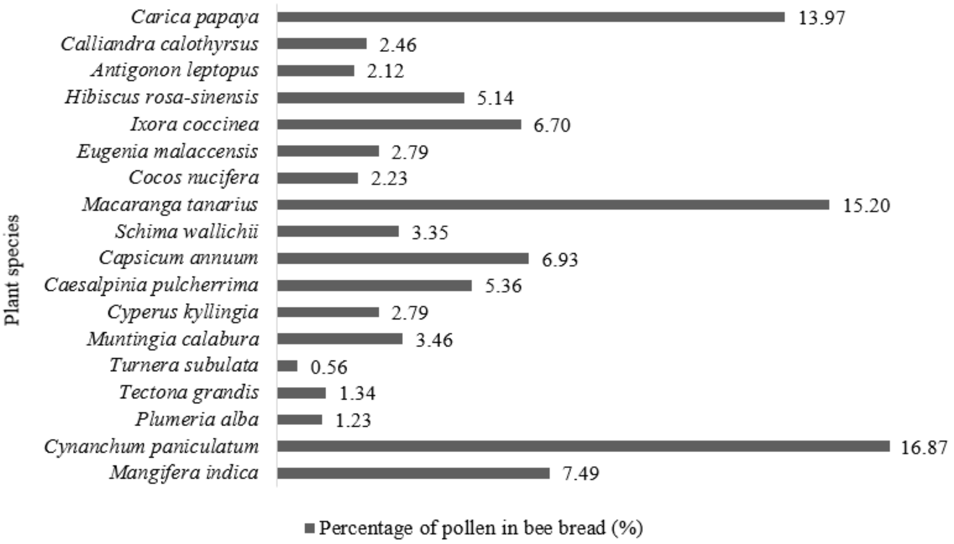

**Figure 2.** Percentage of pollen found in bee bread samples from three *Tetragonula biroi* bee hives

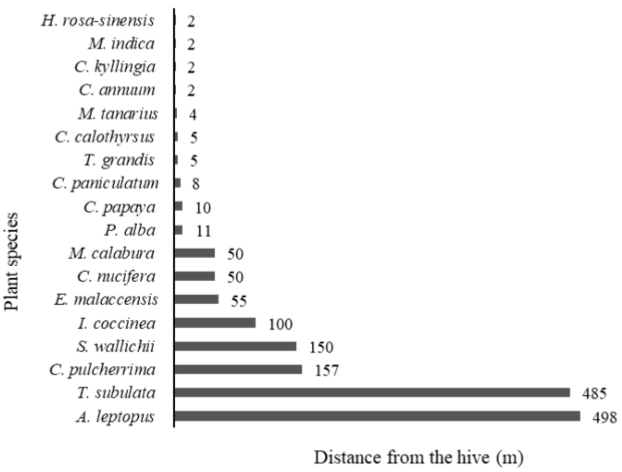

**Figure 3.** Distance of the nearest plant from the hive

Floral constancy is another significant factor influencing floral selection by *T. biroi*. This behavioral tendency, where bees repeatedly visit the same plant species once a profitable resource is identified, enhances pollen transfer efficiency between conspecific flowers and improves foraging learning and speed (Crone et al. 2022). In this study, the relatively high frequency of pollen from specific plants such as *M. calabura* and *C. odorata* suggests a level of constancy that reinforces resource predictability. Visual analysis of pollen grains confirmed their frequent presence and consistent deposition within bee bread storage (Anderson and Mott 2023).

### Distance of forage sources from the bee nest

Most of these pollen plants were located within a short distance of 2-10 m from the nest, allowing easy access for *T. biroi* to forage (Figure 3). Some species, such as *C. nucifera*, *S. wallichii*, and *A. leptopus*, were found at greater distances (50-498 m), indicating the bees' ability to forage over a wider radius when necessary. The diversity of plant species and distances suggest a rich and diverse landscape that supports continuous foraging activity throughout the year.

This study focused on the pollen-foraging preferences of *T. biroi* bees and the distance of floral resources within the Awani Bee Garden. The results showed that *T. biroi* predominantly collected pollen from plant species located closer to the nest. This pattern supports the principle of energy efficiency in foraging behavior, where stingless bees prioritize nearby floral resources to minimize energy expenditure and maximize foraging efficiency. Foraging distance significantly influences resource collection in stingless bees due to their limited flight range and energy reserves (Layek et al. 2024).

Beyond foraging distance, the structure of the surrounding habitat also plays a critical role in determining the availability and accessibility of floral resources for *T. biroi*. Landscapes with greater plant diversity and vertical stratification, such as those that integrate native vegetation with cultivated species, offer improved microclimatic conditions and a more consistent supply of floral resources for pollinators (Poorter et al. 2024). In the urban forest, the presence of flowering shrubs, herbs, and small trees near bee nests has enabled efficient foraging while reducing exposure to predators and environmental stressors. The prominence of *M. indica* in the surrounding landscape illustrates how floral structural arrangement can influence resource selection within short foraging distances.

The identified pollen grains exhibited notable diversity in shape and size, reflecting the range of local flora visited by the bees. Pollen collected and stored as bee bread serves as the primary protein source for the colony (Mărgăoan et al. 2019), and its morphological variation indicates diverse foraging activity. This finding is consistent with Erdtman (1953), who noted that pollen size varies significantly across plant species. The distances traveled by bees to forage for pollen ranged from 2 to 498 m, demonstrating that *T. biroi* can access floral resources within a relatively broad radius. Prastiyo et al. (2024) reported that *T. biroi* has a foraging range of up to 500 m. Although nearby plants are generally preferred, the use of more distant species such as *T. subulata* and *A. leptopus* indicates the bees' capacity for extended foraging flights. These interactions between bees and floral species underscore the ecological importance of conserving flowering plants within the foraging range of stingless bees.

### Correlation between plant distance and pollen foraging preference by *Tetragonula biroi*

The results (Table 1) of the analysis showed a weak negative correlation between plant distance and the percentage of pollen found in bee bread ( $\rho= -0.387$) with $p>0.05$. This indicates that the further the distance of the plant from the colony, the smaller the proportion of pollen collected, but the relationship was not statistically significant.

In addition to distance, the selection of food sources by *T. biroi* is also influenced by other flower characteristics such as color, corolla shape, aroma, and abundant pollen availability. Species such as *C. paniculatum* and *M. calabura* tend to be selected more often because their flower structures are open and easily accessible. This finding is in line with the foraging behavior reported in *T. laeviceps* and *Melipona scutellaris*, which also show a tendency to choose flowers that are easily recognized visually and have high rewards (Nagamitsu and Inoue 2005; Roselino et al. 2016; Maia-Silva et al. 2024). Even in the honey bee *Apis mellifera*, foraging efficiency is highly dependent on visual signals and the quality of nectar sources (Begna et al. 2020; Forster et al. 2023). Although distance is a factor studied, morphological features and flower quality also determine the foraging preference patterns of stingless animals, including *T. biroi*, in maximizing energy efficiency during foraging.

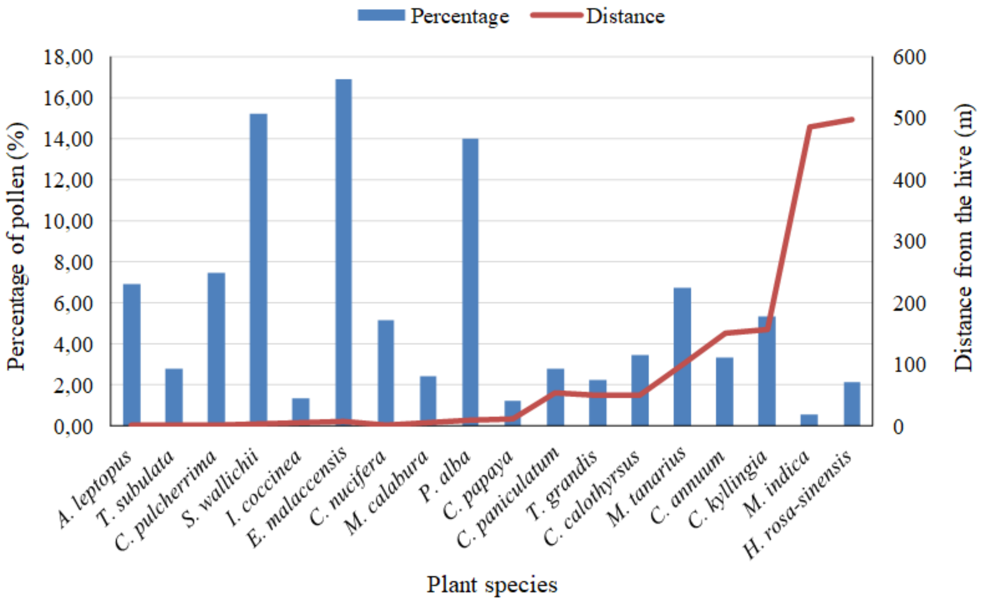

**Figure 4.** Relationship between pollen percentage and distance of floral sources from the hive used by *Tetragonula biroi* in Awani Bee Garden, South Sulawesi, Indonesia

**Table 1.** Spearman correlation results between plant distance and pollen percentage in bee bead

| Variable | Spearman's ρ value | p-value |
|---|---|---|
| Plant distance and % pollen | -0.387 | p>0.05 |

Figure 4 shows the relationship between the percentage of pollen found in bee bread and the distance of plant species from the hive for *T. biroi* in Awani Bee Garden. The results illustrate that most pollen was collected from plant species located at closer distances, such as *C. paniculatum* (8 m, 16.87%), *M. tanarius* (4 m, 15.20%), and *C. papaya* (10 m, 13.97%). In contrast, plants located farther away, such as *T. subulata* (485 m) and *A. leptopus* (498 m), contributed less than 3% each to the total pollen collected. This pattern suggests that *T. biroi* tends to forage predominantly on nearby floral resources, due to energy efficiency and ease of access. However, the presence of pollen from distant plants also indicates flexible foraging behavior when nearby resources are limited or specific nutritional needs arise.

These results align with optimal foraging theory, where *T. biroi* appears to balance energetic costs and floral rewards by selecting resources that are not only nearby but also morphologically favorable. While proximity plays a role, bees often face trade-offs between distance and the quality or quantity of pollen offered by different plant species. For example, *T. carbonaria* has been observed to prefer plants that produce more pollen, even if they are farther away, showing that its foraging range is flexible depending on nutritional needs (Newis et al. 2023). Similarly, landscape-scale studies on *A. mellifera* demonstrate adaptive foraging that maximizes returns under seasonal and spatial resource fluctuations (Bansch et al. 2020). *T. iridipennis* adjusts its foraging behavior based on flower density and variation between patches (Sreekumar et al. 2025). Research by Lichtenberg et al. (2017) further highlights that stingless bees adjust how far they forage based on vegetation density and competition levels. Moreover, a recent study by Kaehler et al. (2024), the foraging ecology of *Tetragonisca fiebrigi* is influenced by sugar concentration and abiotic factors, which affect its flight distance and resource selection. These findings suggest that *T. biroi*, like other stingless bee species, exhibits spatial and sensory flexibility in foraging strategies, shaped by ecological pressures and landscape composition.

## Potential forage sources identified for *Tetragonula biroi* bees

Observation results of the potential forage sources (Table 2) of bees that depend on plant species that provide pollen and nectar for nutrition and resin for the development of their colonies. Among the 18 plant species identified, *M. indica* is the only one giving resin, an important material for nest construction and defense. The diversity of plant resources illustrates the ecological richness of the Awani Bee Garden and supports sustainable foraging behavior.

The diversity of plant families serving as forage sources for bees in the Makassar urban forest reflects a complex vegetation structure that supports dynamic interactions between bees and flowering plants. A total of 17 plant families were recorded, indicating a high level of habitat heterogeneity. This richness not only enhances the floristic composition but also expands the range of forage options available to bees. Bees typically select flowers based on floral morphology and blooming periods (Delgado et al. 2023). Variation in flowering times ensures a continuous supply of forage throughout the year, which is essential for the sustainability of social bee colonies (Gruter et al. 2024).

The distribution of forage functions, pollen, nectar, and resin, shows that many plant species support more than one function, although few provide all three. This indicates that bees must visit a diverse array of plant species to fulfill both their nutritional requirements and nest-building needs. For example, Fabaceae species such as *C. calothyrsus* and *C. pulcherrima* are rich in both pollen (Priyambodo et al. 2023), contributing to colony resilience and increased bee bread production. Bees' ability to exploit various plant species highlights their flexible foraging behavior in response to environmental variability (Prastiyo et al. 2024). Accordingly, urban forest management should prioritize multifunctional plant species and maintain high floristic diversity.

The presence of native species such as *T. grandis*, *C. nucifera*, and *M. calabura* underscores the vital role of locally adapted vegetation in supporting bee ecosystems. Native plants are typically better suited to local climate and soil conditions and often maintain co-evolved relationships with indigenous pollinators (Beckwith et al. 2022). Therefore, conserving and replanting native flora is an effective strategy to sustain bee colonies and promote broader ecosystem stability. Stingless bees, key pollinators in many tropical systems, benefit most when the surrounding landscape provides a diverse and consistently available supply of natural forage (Farfan et al. 2023).

**Table 2.** Potential forage sources for bees around the Awani Bee Garden

| Family | Species | Pollen | Nectar | Resin |
|---|---|---|---|---|
| Solanaceae | *Capsicum annuum* L. | ✓ | ✓ | - |
| Cyperaceae | *Cyperus kyllingia* Endl. | ✓ | ✓ | - |
| Anacardiaceae | *Mangifera indica* L. | ✓ | ✓ | ✓ |
| Malvaceae | *Hibiscus rosa-sinensis* L. | ✓ | ✓ | - |
| Euphorbiaceae | *Macaranga tanarius* L. Müll.Arg. | ✓ | - | - |
| Lamiaceae | *Tectona grandis* L. f. | ✓ | - | - |
| Fabaceae | *Calliandra calothyrsus* Meisn. | ✓ | ✓ | - |
| Lamiaceae | *Cynanchum paniculatum* L. | ✓ | - | - |
| Caricaceae | *Carica papaya* L. | ✓ | ✓ | - |
| Apocynaceae | *Plumeria alba* L. | ✓ | ✓ | - |
| Arecaceae | *Cocos nucifera* L. | ✓ | ✓ | - |
| Muntingiaceae | *Muntingia calabura* L. | ✓ | ✓ | - |
| Myrtaceae | *Eugenia malaccensis* L. | ✓ | - | - |
| Rubiaceae | *Ixora coccinea* L. | ✓ | - | - |
| Theaceae | *Schima wallichii* DC. Korth. | ✓ | ✓ | - |
| Fabaceae | *Caesalpinia pulcherrima* L. Sw. | ✓ | ✓ | - |
| Passifloraceae | *Turnera subulata* Sm. | ✓ | - | - |
| Polygonaceae | *Antigonon leptopus* Hook. & Arn. | ✓ | ✓ | - |

Note: (✓) indicates availability as a forage source for bees, while (-) indicates absence or not identified

**Table 3.** Flowering calendar of bee forage plants around the Awani Bee Garden

| Family | Species | Flowering calendar (month) 2024 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| Solanaceae | *Capsicum annuum* L. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Cyperaceae | *Cyperus kyllingia* Endl. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Anacardiaceae | *Mangifera indica* L. | - | - | - | - | - | ✓ | ✓ | ✓ | ✓ | - | - | - |
| Malvaceae | *Hibiscus rosa-sinensis* L. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Euphorbiaceae | *Macaranga tanarius* L. Müll.Arg. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Lamiaceae | *Tectona grandis* L. f. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Fabaceae | *Calliandra calothyrsus* Meisn. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Lamiaceae | *Cynanchum paniculatum* L. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Caricaceae | *Carica papaya* L. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Apocynaceae | *Plumeria alba* L. | - | - | - | - | - | - | - | - | ✓ | ✓ | - | - |
| Arecaceae | *Cocos nucifera* L. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Muntingiaceae | *Muntingia calabura* L. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Myrtaceae | *Eugenia malaccensis* L. | - | - | - | - | - | - | - | - | ✓ | ✓ | ✓ | - |
| Rubiaceae | *Ixora coccinea* L. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Theaceae | *Schima wallichii* DC. Korth. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Fabaceae | *Caesalpinia pulcherrima* L. Sw. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Passifloraceae | *Turnera subulata* Sm. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Polygonaceae | *Antigonon leptopus* Hook. & Arn. | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

Note: (✓) indicates the flowering period of the plant species, while (-) indicates no flowering observed during that month

### Flowering calendar of forage plants around the Awani Bee Garden

The flowering calendar (Table 3) shows that most food plants flower throughout the year, ensuring a continuous food supply for *T. biroi*. 12 plant species, including *C. papaya*, *A. leptopus*, and *H. rosa-sinensis*, show year-round flowering, which is essential for maintaining colony productivity and stability. In contrast, species such as *E. malaccensis*, *P. alba*, and *M. indica* have a more restricted flowering period, contributing to seasonal variation in resource availability.

Variation in flowering periods among plant species is another key factor influencing foraging behavior. Many plant species in cultivated areas, such as *H. rosa-sinensis*, *I. coccinea*, *M. calabura*, and others, flower year-round, ensuring continuous food availability. This contrasts with *M. indica*, which exhibits a seasonal flowering pattern (Kumar et al. 2017). The asynchronous flowering schedules of different plant species help maintain consistent pollen and nectar availability throughout the year (Tobajas et al. 2024).

Temporal overlap among flowering species is an important ecological trait that supports colony development and minimizes nutritional gaps. Bees depend on sequential blooming patterns, known as phenological complementarity, in which the decline of one species' flowering is offset by the blooming of another (Lemanski et al. 2022). The Awani Bee Garden demonstrates this complementarity through the overlapping flowering periods of *I. coccinea* and *T. subulata* across seasons. The distribution of these plants at varying distances from the nests further allows bees to sustain foraging activity without needing to travel far, especially during periods of floral scarcity.

In addition to pollen and nectar, *T. biroi* requires resin for nest construction, which it collects from various plant sources (Salatnaya et al. 2021). The quality and continuity of food resources are essential for colony health and honey production. Abundant nectar sources contribute significantly to honey yield (Adgaba et al. 2017), and nectar can be found not only in flowers but also in extrafloral structures such as stems (Marazzi et al. 2019). Therefore, effective beekeeping depends on strategic floral resource management. Creating a flowering calendar that incorporates both continuous and seasonal bloomers is essential to ensuring a stable supply of pollen, nectar, and resin. Additionally, relocating bee colonies during periods of floral scarcity can help maintain productivity (Nurnberger et al. 2019). Conservation and planting of diverse flowering plants with complementary blooming periods around cultivation sites are recommended to enhance sustainable forage availability and support the survival and productivity of *T. biroi* and other bee species.

This study concluded that *T. biroi* shows a preference for pollen from flowers located closer to the nest. The bees' foraging strategy prioritizes nearby floral sources, however, they are capable of foraging up to approximately 500 m away when nearby resources are insufficient. The diversity in pollen shape and size collected indicates a wide variety of floral sources. Year-round flower availability and variation in species-specific flowering times are vital for maintaining a continuous food supply. Therefore, maintaining and enriching the diversity of flowering plants, considering both proximity to nests and flowering calendars, is crucial to supporting the sustainability of *T. biroi* populations in both managed and natural ecosystems. Findings suggest that optimal planting distance can enhance stingless bee pollination efficiency. These findings provide ecological insight into how spatial floral arrangements affect pollen intake, and can inform the design of pollination-friendly landscapes in agroforestry and meliponiculture systems to enhance foraging efficiency and colony resilience. Promoting floral diversity within a 10-50 m radius may optimize energy use and improve pollination services by *T. biroi*. These findings support the application of floral landscape planning for stingless bee conservation and agricultural crop pollination strategies.

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