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Diversity and community structure of insects on sugar palm and their correlation with abiotic factors in Tanah Datar Regency, West Sumatra Province, Indonesia

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ABSTRACT

Sugar palm (*Arenga pinnata* Merr.) agroecosystems provide important ecological functions in tropical agricultural landscapes, particularly as habitats for pollinator insects and other arthropod communities. However, information regarding insect diversity and the influence of environmental factors on pollinator activity in sugar palm agroecosystems remains limited in Indonesia. This study aimed to evaluate insect diversity and community structure, and to examine the relationships between abiotic factors and insect abundance in sugar palm agroecosystems in Tanah Datar Regency, West Sumatra, Indonesia. Field observations were conducted in Lintau Buo and Sungayang Districts in 2025. Insects associated with sugar palm inflorescences were sampled during morning and afternoon observation periods using direct observation and sweep net methods. Community structure was analyzed using diversity, evenness, richness, and dominance indices. At the same time, the effects of abiotic variables on pollinator abundance were assessed using Negative Binomial Generalized Linear Models (GLM) and Spearman rank correlation analysis. A total of 2,297 insect individuals were recorded, consisting of 1,858 pollinator insects and 439 visitor insects belonging to 13 genera. Pollinator communities were dominated by *Apis* spp., *Vespa* sp., *Polyrhachis* spp., *Episyrphus* sp., and *Tetragonula* spp. Diversity analysis indicated moderate insect diversity, with high evenness and low dominance, suggesting relatively stable ecological conditions within the agroecosystem. Negative Binomial GLM revealed that rainfall significantly reduced pollinator abundance (Estimate = −0.084 ± 0.021 SE, $p < 0.001$), while relative humidity also negatively affected pollinator activity ($p = 0.006$). Spearman correlation analysis confirmed a strong negative relationship between rainfall and pollinator abundance ($r_s = -0.82$, $p < 0.01$). These findings demonstrate that sugar palm agroecosystems support diverse insect communities and highlight the importance of environmental conditions in regulating pollinator activity within tropical agroforestry systems.

Key words: agroecosystem, *Arenga pinnata*, biodiversity, pollinator insects, tropical agroforestry

INTRODUCTION

In tropical agroecosystems of Indonesia, *Arenga pinnata* Merr. (Arecaceae) is a keystone multipurpose palm whose products support rural livelihoods and regional economy. The species yields palm sugar from sap, fibers for industrial applications, and structural and culinary by-products from leaves and trunk, reinforcing its socio-economic significance in South and Southeast Asia, including Indonesia. Beyond direct economic value, *A. pinnata* contributes to ecosystem stability through soil stabilization via deep, dense root systems and canopy-mediated microclimate buffering, which support local biodiversity and watershed

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protection in fragile landscapes (Sharma & Abrol, 2015; Medán & Devoto, 2017; Suhendra et al., 2025). In West Sumatra, sugar palm cultivation and associated agroforestry practices occupy substantial land areas and contribute to regional productivity, with Tanah Datar Regency acting as a notable production hub in highland and peri-urban landscapes.

Learning about the interrelations between plants, insects and climate can be more easily understood within the Tanah Datar region of South Sumatra. This is because smallholders cultivate various types of palm plants in landscapes that consist of semi-wild palms and customary polycultures, alongside fragmented patches of forest. The layout of the landscape determines the types of pollinators and the services they offer such as providing pollination and/or yielding nectar or pollen. This can have an effect on the stability of yields as well as the quality of the fruit and seeds produced by the palms, especially with the variability in climate (Younas et al., 2022; Rajpurohit et al., 2024). In light of climate change and other man-made emergencies, it is crucial to accurately assess the communities of insects that interact with *A. pinnata* in order to promote biodiversity and the functionality of palm ecosystems (Koneri et al., 2024; Coates et al., 2024).

The ecology of the interrelationships formed by the *A. pinnata* and its pollinators along with the reproductive features of *A. pinnata*, highlight the importance of insect pollinators. *A. pinnata* is monoecious and displays protandrous flowering. This results in the male and female flowers of the palm flowering at different times to help reduce self-fertilization, but it also increases the reliance of the palm on insect pollinators for the fruit and seeds. The flowers of the palm provide rewards to its pollinators and thus, the community of foragers is very diverse and can include members of Hymenoptera, Diptera and other orders as well. Studies conducted on other palm species have shown that the dominant community of pollinators are bees (Apidae and Megachilidae) but can change depending on the characteristics of the landscape, climate, and the display of flowers, thus showing the necessity of studies on the Arenga and closely related taxa (Wang et al., 2019; Raffiudin et al., 2024; Coates et al., 2024).

A crucial, often neglected, dimension is how abiotic factors – air temperature, relative humidity, and precipitation – interact with pollinator activity and visitor composition. In ectothermic insects, these microclimatic variables impose physiological and behavioral thresholds that shape visitation rates, foraging duration, and flight capabilities, ultimately constraining pollination efficiency and palm productivity. Tropical agroecosystems offer a natural laboratory for exploring such interactions, as thermal regimes, humidity, and rainfall patterns systematically shift with altitude, thereby modulating both host phenology and pollinator assemblages. Several studies in tropical and subtropical systems report clear links between abiotic gradients and pollinator activity, yet comprehensive, quantitative syntheses for palm-centered systems in Indonesia remain scarce. Consequently, there is a recognized gap in understanding how abiotic drivers shape the legitimate pollinator guilds versus non-pollinating visitors to sugar palms in Tanah Datar (Koneri et al., 2024; Febriansyah et al., 2025; Syahputri et al., 2025).

In the Tanah Datar region, the knowledge gap with farm-management practices (including polyculture vs. monoculture, silvicultural practices, and pest monitoring) relates to microclimate and landscape structures to determine the diversity and behavioral patterns of pollinators and their activities. Optimal management of the agroecosystem involves the study of insect populations at the various levels (strata) of the ecosystem, which coupled with diverse farming practices, helps to understand the framework of the management practices and their impact on the pollination services for the communities. This helps in the conservation of the diversity and the resilience of the *Arenga pinnata* (*A. pinnata*) palms, and in the formulation of conservation and agroecological methodologies for adaptive management of the climate variability to enhance the yield of the palms (Ikhsan et al., 2024; Rajpurohit et al., 2024; Coates et al., 2024).

For this study, the main goals are broken down into three interrelated ecological studies. The first aims to study the insect visitors to *Arenga pinnata* and assess their diversity, richness, and develop a community composition (including the Shannon-Wiener index and community evenness) for distinct areas in Tanah Datar Regency in West Sumatra. The second aims to identify the different types of (non-pollinating) floral visitors to inflorescence of *Arenga pinnata* and legitimate pollinators, and their visiting patterns (temporal visit frequency and visit durations). The third aims to explore the relationship between temperature, humidity, and rainfall, and the insect species in the study areas.

MATERIALS AND METHOD

Study Area and Sampling Design

The investigation was conducted from January to May 2025 across the principal sugar palm production centers in Tanah Datar Regency, West Sumatra, Indonesia, i.e.: the Sungayang and Lintau Buo districts. A purposive sampling strategy was employed to capture representative agroecological contexts within the regency's sugar palm landscapes. Within each district, five distinct smallholder farms with actively flowering *A. pinnata* trees and accessible mature male inflorescences undergoing anthesis were selected, yielding ten study plots. This design aligns with prior palm-pollination field schemes that emphasize functional differentiation across management contexts and microhabitats and provides sufficient statistical power to detect differences in insect communities among districts and farming practices (Campbell et al., 2018; Wang et al., 2019).

Site characterizations including precise geographic coordinates and habitat descriptors were recorded with a handheld GPS. Microhabitat attributes (e.g., surrounding vegetation structure, tree density, and understory cover) were cataloged to facilitate habitat–pollinator analyses and to contextualize abiotic gradients that may influence insect activity patterns (Koneri et al., 2024; Coates et al., 2024; Raffiudin et al., 2024).

Abiotic Factors

Abiotic factors were gathered at the same time as insect sampling to establish possible relationships between the environment and pollinators. Temperature, air, and insect sampling humidity, and rain were measured for each sampling event. Temperature and humidity were measured using a calibrated digital thermohygrometer placed 1.5 m off the ground and took measurements every 30 minutes. Daily rain measurements were made using portable rain gauging devices and were cross-checked with BMKG reports to ensure the measurements were conducted within the timeframe of the insect sampling (BMKG, 2026). Much of the existing literature on pollination ecology emphasizes the responses of ectothermic pollinators to temperature and humidity, thus, combining visitation metrics with microclimate measurements is justified (Sharma & Abrol, 2015; Rajpurohit et al., 2024; Coates et al., 2024).

Insect Sample Methodology and Guild Assignments

In order to capture both the canopy and understory insect communities, and to address biases of multi-method sampling, a harmonized multi-method sampling approach was used within each sampling site. This approach was modeled off of the recent synthesis of best-practice protocols for sampling pollinators in tropical settings which recommended using integrated methods in order to improve the completeness of taxonomy and capture uncommon and/or ephemeral taxa (Prado et al., 2017; McCravy, 2018). Four insect collections were conducted at each research site, each separated by a one-month interval.

1) Active Visual Observation and Sweep Netting

Visual observations were conducted during five consecutive days per site, divided into three daily windows reflecting peak insect activity: morning (08:00–10:00), midday (12:00–14:00), and afternoon (16:00–18:00) WIB, following protocols used in comparable palm-pollination studies (Prado et al., 2017; Novianto, 2022; Coates et al., 2024). Observations focused exclusively on male inflorescences at anthesis, when pollen production and insect visitation are typically highest. Insect visitors were recorded upon landing on male flowers and contacting floral structures, particularly pollen-bearing organs. Observers maintained a distance of 1.0–1.5 m from the inflorescences and recorded visit frequency (visits per unit time) and visit duration (time spent in contact with floral organs). After each observed foraging event, specimens were captured using a standard sweep net (30 cm diameter, 100 cm handle) to avoid recounting individuals and to facilitate subsequent taxonomic identification. Sweep-netting is recognized as an effective method for systematically sampling diverse arthropod assemblages associated with tropical flowering plants (Kent et al., 2019).

2) Passive Trapping (Yellow Sticky Traps and Malaise Traps)

To catch various flying anthophilous insects, especially Diptera and Hymenoptera, three yellow sticky traps (20 cm × 25 cm) were placed inside the crown of sampled palms at a height of 2–3 m. In each farm plot, a single Malaise trap (Samaranayake & Costamagna, 2019; Graham et al., 2023) was set at ground level. This trap was meant to provide information on the flight activity of the canopy and understory, and to help the canopy-focused traps. For each sampling cycle, traps were set for 48 hours, and specimens were stored for later identification.

2) Functional Guild Classification

Insects were classified into two functional guilds by direct behavioral observation on male oil palm inflorescences and by their status as pollen carriers. For oil palm inflorescence foraging insects that were found to be carrying pollen grains on their bodies (a find confirmed by microscopic examination), potential status as pollinators was assigned since observations were made on male oil palm inflorescences. All other insects were classified as non-pollinating visitors if they were seen on oil palm inflorescences but were not interacting with the reproductive structures and/or did not have pollen on their bodies. This classification was made to indicate their probable role in transport of oil palm pollen.

Insects collected by sweep nets and malaise traps were preserved in 70% ethanol. Sticky traps were processed using gentle solvents to maintain the key morphological traits required for identification. In both cases, the taxonomic focus was at the genus level.

Data Processing and Statistical Analyses

Diversity and community structure were quantified using standard alpha-diversity indices, including richness (S), Shannon-Wiener diversity (H'), and Pielou’s evenness (E). Simpson’s dominance (D) was computed to detect species dominance patterns. All analyses were conducted in R (v4.3.1) with the vegan package, supplemented by SPSS Statistics (v26) for supplementary multivariate tests as appropriate. Pollinator abundance was analyzed using a Poisson GLM and, subsequently, a Negative Binomial GLM to account for overdispersion in the count data. Spearman's rank correlation was applied to assess relationships between abiotic variables and insect abundance.

RESULTS

The study investigated ten sugar palm agroecosystem sites in Tanah Datar Regency, West Sumatra, capturing environmental heterogeneity and land-use intensity typical of smallholder mosaic landscapes. Field observations documented that *Arenga pinnata* stands occur in polycultures with *Theobroma cacao, Hevea brasiliensis, Cocos nucifera*, rice fields, and other plant communities, with most populations managed traditionally rather than under intensive agronomic regimes (Table 1). This heterogeneity provides a natural experimental backdrop to explore how abiotic gradients shape insect visitation and pollination dynamics in tropical palm systems (Withaningsih et al., 2023; Koneri et al., 2024).

Table 1. Geographic coordinates and planting patterns of sugar palm agroecosystems

District	Coordinate Points	Planting Pattern
Lintau Buo	0° 22' 56.269" S 100° 39' 33.666" E	Polyculture with cocoa
	0° 24' 39.377" S 100° 44' 18.595" E	Polyculture with rubber and shrubs
	0° 22' 53.861" S 100° 40' 39.521" E	Polyculture with rubber and coconut
	0° 22' 53.965" S 100° 40' 39.513" E	Monoculture and shrubs
	0° 22' 53.96" S 100° 40' 39.492" E	Monoculture
Sungayang	0° 23' 40.376" S, 100° 38' 16.584" E	Polyculture with cocoa
	0° 22' 50.214" S, 100° 38' 50.165" E	Polyculture with cocoa and shrubs
	0° 23' 33.652" S, 100° 38' 43.728" E	Polyculture with rice and fruit plants
	0° 22' 52.453" S, 100° 38' 58.945" E	Monoculture
	0° 22' 31.055" S, 100° 36' 18.389" E	Monoculture

A. Environmental Characteristics of the Sugar Palm Agroecosystem

The ten agroecosystem sites in Lintau Buo and Sungayang Districts illustrate a blend of monoculture and polyculture systems nearby vegetation that creates habitat diversity. The distribution of cocoa, rubber, and coconut trees, rice fields, shrubs and mixed fruit trees demonstrate patterns of structural and species diversity that alter (increase or decrease) the availability of resources for floral visitors and pollinators (Montagnana & Campos, 2020; Withaningsih et al., 2023; Koneri et al., 2024).

The two districts had different microclimates over the study period (Fig. 1). Lintau Buo was relatively dry and warm (precipitation in the 10-14 mm range, temperatures around 29°C, humidities in the low 59%-64% for the study area). Sungayang was wetter (precipitation in the 20-31 mm range), cooler (precipaughters in the 27-21.5° range), and more humid (68%-80%). These differing climates are the results of differences in agroecosystems and vegetation densities and the variable nature of the relief, setting out abiotic filters which determine the insect activity in flowering sugar palms (Withaningsih et al., 2023; Koneri et al., 2024; Cao et al., 2025).

The primary abiotic factors, rainfall and humidity, are expected to affect the ability of insects to fly, the rate of nectar secretion and the floral resources. Pollinators are expected to be more active with lower humidity and temperature, and that high humidity and rainfall are expected to limit pollinator flight activity and visitation, affecting composition and function of the pollinator community (Koneri et al., 2024; Cao et al., 2025). This is what is expected and is reflected in the patterns of insect visitation presented in the following sections.

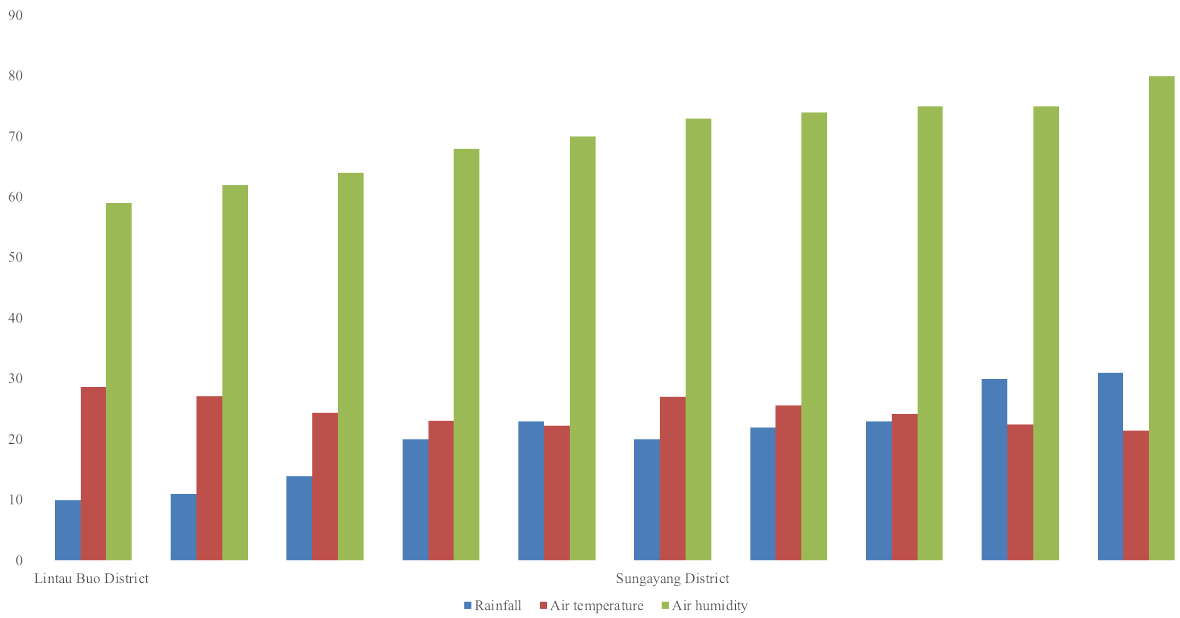

Figure 1. Average rainfall, air temperature, and relative humidity recorded in sugar palm agroecosystems in Lintau Buo and Sungayang districts.

B. Diversity and Composition of Insects Associated with Sugar Palm

Across the survey, 2,297 insect individuals were recorded, comprising 1,858 pollinators and 439 visitors. Pollinators assembled from five genera: *Apis* spp., *Vespa* sp., *Polyrhachis* spp., *Episyrphus* sp., and *Tetragonula* spp. Visitors comprised eight genera: *Anopheles* spp., *Spodoptera* spp., *Tipula* spp., *Macroglossum* spp., *Actia* spp., *Anomala* spp., *Blaps* spp., and *Aphrophora* spp. This composition demonstrates a relatively diverse pollinator and visitor community associated with sugar palm flowers in these tropical agroecosystems (Prado et al., 2020; Withaningsih et al., 2023).

The Shannon-Wiener diversity index (H') values were 1.55 for pollinators and 1.69 for visitors, indicating moderate diversity for both groups within semi-natural to semi-managed tropical agroecosystems. Pollinator evenness was notably high (E = 0.95), suggesting a relatively balanced distribution of pollinator genera across the assemblage. Visitors showed slightly lower evenness (E = 0.80), indicating greater dominance by a subset of visitor taxa (e.g., *Anopheles* spp. and *Spodoptera* spp.). Domination indices were low for both groups (C = 0.23 for pollinators; C = 0.24 for visitors), suggesting that no single genus dominates the communities (Montagnana & Campos, 2020; Prado et al., 2020; Withaningsih et al., 2023).

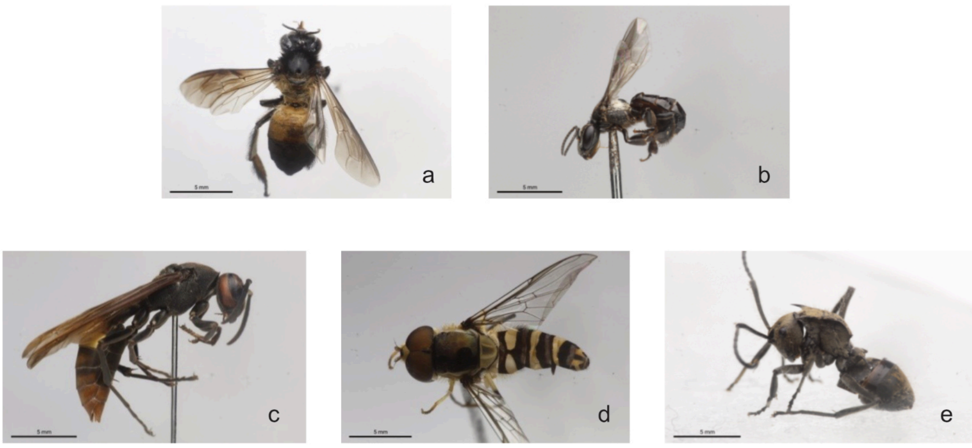

Figure 2. Sugar palm Insect pollinators (a) *Apis* spp. (b) *Tetragonula* spp. (c) *Vespa* sp. (d) *Episyrphus* sp. (e) *Polyrhachis* spp.

Among pollinators, *Apis* spp. accounted for the largest share (545 individuals), followed by *Vespa* sp. (522), *Polyrhachis* spp. (310), *Episyrphus* sp. (266), and *Tetragonula* spp. (215). Among visitors, *Anopheles* spp. (164) was the most abundant, followed by *Spodoptera* spp. (95) and *Tipula* spp. (70). The pattern suggests a pollinator community dominated by social Hymenoptera and Diptera visitors, with predatory wasps co-occurring alongside visiting bees for nectar and pollen resources (Montagnana & Campos, 2020; Prado et al., 2020; Withaningsih et al., 2023).

The moderate Shannon values, coupled with high pollinator evenness and relatively low dominance, suggest potential functional stability. Functional redundancy among pollinator guilds (*Apis* spp., *Vespa* sp., *Tetragonula* spp., *Episyrphus* sp., *Polyrhachis* spp.) supports stable pollination services under fluctuating environmental conditions. The presence of a richer visitor guild indicates that sugar palm agroecosystems provide floral resources across a wider temporal window, supporting multiple trophic interactions and potential pest suppression through predator/parasitoid activity (Montagnana & Campos, 2020; Withaningsih et al., 2023; Koneri et al., 2024).

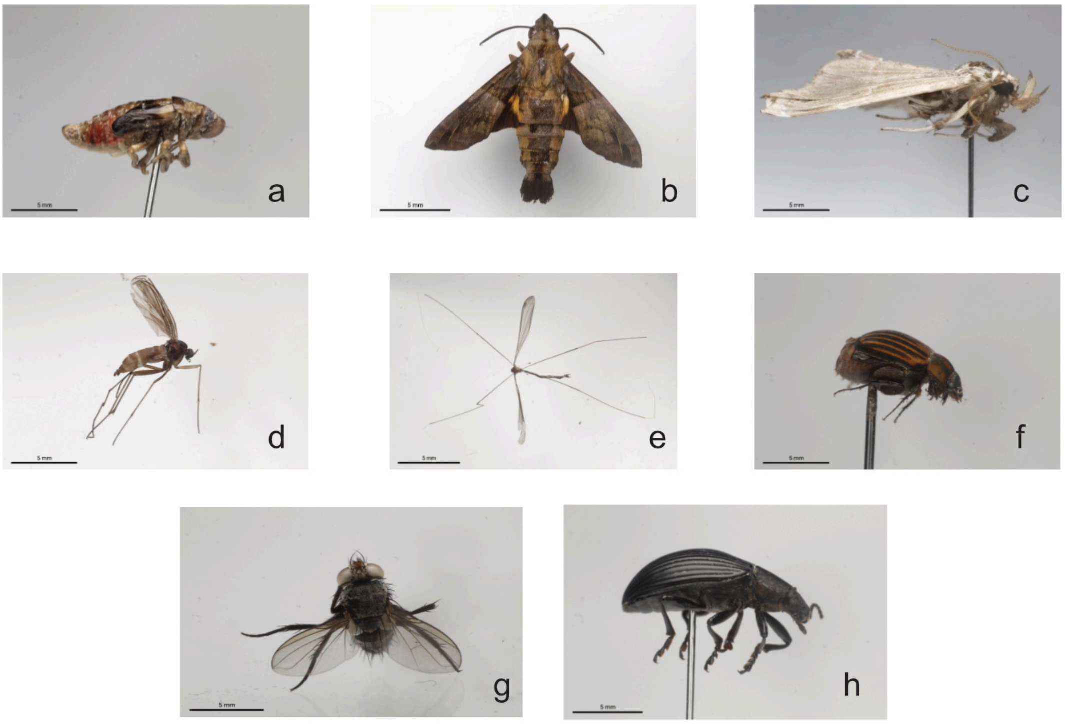

Figure 3. Sugar Palm Insect visitors (a) *Aphrophora* spp. (b) *Macroglossum* spp. (c) *Spodoptera* spp. (d) *Anopheles* spp. (e) *Tipula* spp. (f) *Anomala* spp. (g) *Actia* spp. and (h) *Blaps* spp.

C. Temporal Patterns of Insect Activity

Temporal observations indicate higher insect activity during morning hours (07:00-09:00 WIB) than in the afternoon (15:00-17:00 WIB across both districts. This morning peak aligns with classical pollination ecology expectations in tropical systems, where cooler conditions, reduced evaporative stress, and higher nectar secretion rates optimize foraging efficiency, flight performance, and nectar uptake (Koneri et al., 2024; Cao et al., 2025).

Pollinator visitation frequency was consistently higher in the morning, with longer visitation durations during the morning than in the afternoon. Tables 2 and 3 summarize abundance and visitation dynamics, showing higher pollinator counts in morning blocks and relatively stable visitation duration across periods, albeit slightly longer in the morning for several taxa. This pattern supports the inference that early-day windows maximize pollination service delivery in these agroecosystems (Withaningsih et al., 2023; Koneri et al., 2024; Cao et al., 2025).

Table 2. The types of insects obtained during the morning and evening observation period at the research site

District	Coordinate Points	Number of Insects in the Observation Period								Total
		1		2		3		4		
		M	A	M	A	M	A	M	A	
Lintau Buo	Insect pollinators		148	132	118	118	104	182	157	1.124
	Insect Visitors	41	36	28	24	21	18	36	29	233
Sungayang	Insect pollinators	152	139	121	109	110	96	171	146	1.044
	Insect Visitors	37	31	24	21	18	15	33	27	206
	Total	395	354	305	272	267	233	422	359	2.297

Table 3. Frequency of pollinator insect visits

Research location	Month to	07.00-09.00 WIB		15.00-17.00 WIB	
		Number of pollinating insect visits	Duration (sec)	Number of pollinating insect visits	Duration (sec)
Lintau Buo District	1	44	18.21	40	17.64
	2	31	17.86	28	17.22
	3	27	17.45	24	16.91
	4	49	17.12	43	16.58
Sum		151	70.64	135	68.35
Average		37.75	17.66	33.75	17.09
Sungayang District	1	39	18.05	36	17.52
	2	28	17.70	24	17.16
	3	24	17.33	22	16.84
	4	43	16.98	38	16.41
Sum		134	70.06	120	67.93
Average		33.50	17.52	30.00	16.98

While both districts exhibited a morning peak, absolute abundances were higher in Lintau Buo, consistent with its warmer, drier microclimate, which may favor certain pollinator taxa operating under less humid, thermally conducive conditions. Sungayang's higher rainfall and humidity may impose additional constraints on activity, contributing to comparatively lower pollinator visitation rates during the afternoon and possibly dampening overall visitation efficiency (Withaningsih et al., 2023; Koneri et al., 2024; Cao et al., 2025).

Figure 4 illustrates the relationship between rainfall and pollinator abundance, highlighting the negative association between precipitation and pollinator visitation. This figure underpins the idea that rainfall acts as a strong abiotic filter, restricting pollinator activity in these systems, and that rainfall explains a substantial portion of the variance in pollinator abundance across sites and times (Withaningsih et al., 2023; Koneri et al., 2024).

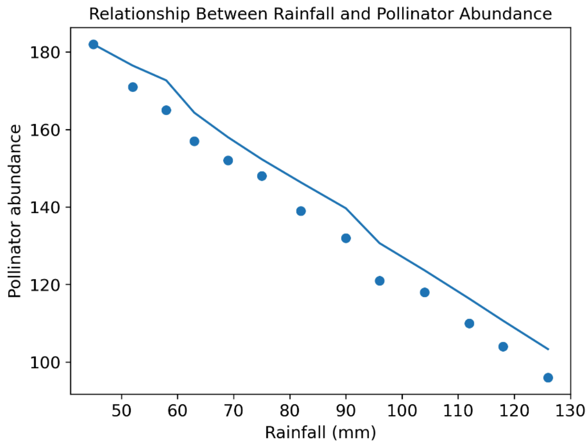

Figure 4. Scatterplot illustrating the relationship between rainfall and pollinator abundance in sugarpalm agroecosystems in Tanah Datar Regency.

D. Relationship Between Abiotic Factors and Insect Abundance

The Negative Binomial Generalized Linear Model (GLM) was employed to quantify how rainfall, relative humidity, and air temperature shape pollinator abundance. The model indicated that rainfall and relative humidity exert significant negative effects on pollinator abundance, whereas air temperature showed a weak positive relationship. Specifically, rainfall and humidity reductions were statistically significant ($p < 0.01$ and $p = 0.006$, respectively), while air temperature exhibited a modest positive effect ($p = 0.035$). The model also included a fixed effect for observation period (afternoon) and district, revealing lower abundance in the afternoon and in Sungayang relative to Lintau Buo. These results point to rainfall and humidity as primary abiotic filters limiting pollinator activity in these sugar palm agroecosystems (Withaningsih et al., 2023; Koneri et al., 2024).

Spearman Rank Correlations: Analysis of the results from the General Linear Model (GLM) using non-parametric statistics showed that rainfall and relative humidity had a strong negative correlation with abundance of pollinators ($r_s \approx -0.82$ and -0.67, $p < 0.01$ and < 0.05), and air temperature had a very weak positive correlation ($r_s \approx 0.31$, $p > 0.05$). There was a strong positive correlation between the abundance of pollinators and that of visitors ($r_s \approx 0.79$, $p < 0.01$), implying that the environmental conditions that enable high abundance of pollinators are the same that enable high abundance of other taxa visitors (Withaningsih et al., 2023; Koneri et al., 2024).

Table 4. Negative Binomial GLM Explaining the Effects of Abiotic Factors on Pollinator Abundance in Sugar Palm Agroecosystems

Variables	Estimate ± SE	z-value	p-value	Interpretation
Intercept	3.106 ± 0.528	5.88	<0.001	Significant baseline abundance
Rainfall	-0.084 ± 0.021	-3.98	<0.001	Significant negative effect
Relative humidity	-0.041 ± 0.015	-2.71	0.006	Significant negative effect
Air temperature	0.028 ± 0.013	2.11	0.035	Weak positive effect
Observation period (afternoon)	-0.061 ± 0.022	-2.77	0.005	Pollinator abundance decreased in the afternoon
District (Sungayang)	-0.049 ± 0.024	-2.04	0.041	Lower abundance compared with Lintau Buo

The results indicate that among the different abiotic factors, including rainfall and humidity, the rest shaped the structure and the level of the pollination services in the sugar palm agroecosystems. The weak influence of temperature indicates that pollinators may be active across a wider temperature range in the tropics, which may be extended to the moisture and precipitation, and the rest may reflect some positive association. The strong positive association between visitors and pollinators indicates that the rest may reflect some positive association. Visitors (beyond the main pollinators) may represent herbivores, predators, and many different interactions that may influence the overall function of the ecosystem and its resilience (Montagnana & Campos, 2020; Cao et al., 2025).

The sugar palm agroecosystem is a interacts across numerous trophic levels systems that integrates both pollinators and a range of visitor guilds.. Predatory wasps, such as wasps of the genus Vespa, and hoverflies of the genus Episyrphus, may contribute to pest control; herbivorous guilds of Spodopteran and Anomalans may related to damage of host plants. However, a diverse and even distribution of pollinators will facilitate a shift from high reliance on one visitor guild, and may improve system safety across the climate spectrum. The observed patterns emphasize habitat complexity and floral resource continuity as critical management levers to sustain pollination and indirect ecosystem services in tropical agroforestry systems (Montagnana & Campos, 2020; Withaningsih et al., 2023; Koneri et al., 2024).

Table 5. Spearman Rank Correlation Between Abiotic Variables and Insect Abundance

Variables	Pollinator abundance (rs)	p-value	Visitor abundance (rs)	p-value	Correlation strength
Rainfall	-0.82	<0.01	-0.74	<0.05	Strong negative
Relative humidity	-0.67	<0.05	-0.61	<0.05	Moderate negative
Air temperature	0.31	>0.05	0.27	>0.05	Weak positive
Pollinator vs visitor abundance	0.79	<0.01	-	-	Strong positive

DISCUSSION

The sugar palm agroecosystem supports a moderately diverse pollinator network dominated by Hymenoptera and Diptera, with functional redundancy across multiple taxa. This redundancy enhances pollination resilience in the face of environmental fluctuations and anthropogenic disturbance, echoing findings from tropical agroforestry contexts where structural complexity supports diverse pollinator guilds and stable pollination services (Montagnana & Campos, 2020; Withaningsih et al., 2023; Koneri et al., 2024).

The greater richness in visitor taxa compared to pollinator taxa implies that sugar palm inflorescences may support a broader range of visitors, thereby enabling temporal niche partitioning to extend resource use to crepuscular and nocturnal periods, as suggested by the occurrence of Macroglossum spp. and other nocturnal and crepuscular taxa. The visitor, pollinator, and visitor-pollinator assemblage richness is in accordance with the theories that the structural complexity of the agroecosystem enhances the richness of assemblages with partitioned temporal niches (Withaningsih et al., 2023).

Rainfall has been identified as the primary abiotic factor explaining variation in pollinator density, whilst humidity acted as a strong negative filter. This has implications for the climate change scenario in tropical Southeast Asia, where the patterns of rainfall are expected to be more erratic and extreme. It may lead to the degradation of pollination networks if heterogeneity is not maintained in the ecosystems (Withaningsih et al., 2023; Koneri et al., 2024). The pronounced morning peak in pollinator density indicates that agroecosystem management may be adjusted to synchronize pest management and other maintenance and flowering activities with peak visitation to maximize the benefits of ecosystem services. The clearly observable, diurnal pattern reinforces the rationale for conserving floral resources throughout the diurnal timescape (Koneri et al., 2024; Cao et al., 2025).

The results advocate for conserving vegetation heterogeneity around sugar palm stands, including flowering shrubs and mixed cropping patches that sustain alternative floral resources and nesting substrates. These habitat features support pollinator diversity and ecosystem resilience, particularly in landscapes undergoing fragmentation or intensification. The integration of semi-natural habitats and diverse plant assemblages within sugar palm landscapes can sustain pollination services and subordinate pest regulation services, contributing to sustainable production systems in tropical regions (Withaningsih et al., 2023; Koneri et al., 2024).

The revised results synthesize environmental heterogeneity, insect diversity and composition, temporal activity patterns, and abiotic drivers to present a coherent narrative about pollination services in sugar palm agroecosystems of West Sumatra. The evidence consistently points to rainfall and humidity as primary constraints on pollinator abundance, with morning activity peaks supporting efficient pollination windows. Habitat complexity and mosaic land-use patterns emerge as crucial determinants of pollination resilience, with implications for sustainable management in tropical agroforestry systems. The findings align with broader theoretical and empirical work on pollination ecology, nectar microbiology, and agroecology, and underscore the value of maintaining diverse, semi-natural habitats within agricultural landscapes to sustain ecosystem services under climate variability.

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CONCLUSIONS

The Sugar palm (*Arenga pinnata* Merr.) agroecosystems in Tanah Datar Regency supported moderately diverse insect communities characterized by relatively high pollinator abundance, balanced community structure, and low dominance levels. A total of 2,297 insect individuals belonging to 13 genera were recorded, with pollinator insects dominating the assemblage. The predominance of *Apis* spp., *Vespa* sp, *Polyrhachis* spp., *Episyrphus* sp., and *Tetragonula* spp. highlight the ecological importance of sugar palm flowers as essential nectar and pollen resources within tropical agroforestry landscapes.

Through community structure analysis, it was found that the agroecosystem provided a relatively stable environment that harbored a number of functional categories of insects such as pollinators, herbivores, and predatory insects. The activities of the pollinators were greatly impacted by environmental factors such as rainfall and relative humidity. The results of

Negative Binomial GLM analysis and Spearman correlation analysis clearly showed that higher amounts of rainfall led to a lower abundance of the pollinators.

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