

Research Article



## Ground-Dwelling Insects as Bioindicators for Post-Mining Restoration in Pangkep Regency, South Sulawesi, Indonesia

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### ARTICLE INFO

#### Article history:

Received May 31, 2025

Received in revised form August 7, 2025

Accepted January 7, 2026

Available Online February 11, 2026

#### KEYWORDS:

Biodiversity,  
Clay,  
Environment,  
Insect,  
Limestone,  
Reclaimed land

### ABSTRACT

Ground-dwelling insects are key indicators of ecosystem health due to their roles in decomposition, nutrient cycling, and the dynamics of food webs. Post-mining lands often suffer from environmental degradation, requiring effective reclamation strategies. This study assessed the relationship between microclimate and ground-dwelling insect composition in reclaimed limestone and clay mining sites at PT Semen Tonasa, Pangkep Regency, South Sulawesi, Indonesia. Insects were sampled using pitfall traps across sites with different reclamation years. Diversity indices Shannon-Wiener ( $H'$ ), richness ( $R$ ), evenness ( $E$ ), dominance ( $D$ ), correlation analysis, and principal component analysis (PCA) were used to evaluate patterns. A total of 23,294 individuals representing 36 species, 26 families, and nine orders were recorded. Dominant species included *Dolichoderus thoracicus* and *Carebara diversa*, indicating high ecological adaptability. The highest diversity ( $H' = 2.09$ ) and richness ( $R = 3.32$ ) were found in the 2017 clay site, while the 2018 limestone site had the highest evenness ( $E = 0.85$ ) and dominance ( $D = 0.36$ ). Correlation analysis showed that soil temperature and humidity were significantly positively associated with insect diversity ( $r > 0.60$ ,  $p < 0.05$ ). PCA revealed air temperature, humidity, soil pH, and light intensity as key factors influencing insect communities, accounting for 52.08% (PC1) and 28.63% (PC2) of the variance. These findings highlight the importance of microclimate-informed management for successful post-mining land restoration.



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## 1. Introduction

Climate change and anthropogenic activities, such as mining, significantly impact degraded forest ecosystems (Menta & Remelli 2020). These disturbances alter microhabitat structures, disrupt ecological interactions, and reduce biodiversity across trophic levels. Insect populations, especially those closely associated with soil and litter layers, are among the first to respond to these environmental shifts. Ground-dwelling insects play a crucial role in supporting soil health and ecosystem function by recycling nutrients and serving as indicators of environmental quality. These insects inhabit the ground-dwelling or litter layers and interact with environmental factors, including temperature, humidity,

and nutrient availability. In post-mining areas, ground-dwelling insects face significant challenges adapting to microclimate conditions that differ from their original habitat (Pietrzykowski 2019). The distribution and diversity of these insects are crucial for evaluating the success of forest reclamation programs and offering insights into their role in the recovery of degraded forest ecosystems (Bandyopadhyay & Maiti 2019).

A paucity of research has been conducted on how insects adapt to climate change and microclimate conditions in reclaimed land, which has a direct impact on species diversity and composition. Schowalter (2022) states that the abundance of insect species is influenced by their ability to maintain survival, adapt to varied habitats, and possess sufficient reproductive capabilities. The interaction between microclimate and ground-dwelling insects in post-mining areas remains largely unexplored, particularly in terms of how surface

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temperature, soil moisture, and light intensity influence the distribution of specific species (Prakash & Budhwan 2024). Particular insect species may survive or thrive in limestone and clay mining areas that have undergone severe degradation due to mining activities, only to be reclaimed into areas that support sustainability. Mining activities cause ecological damage, including habitat loss (Shanmukha *et al.* 2024).

Reclamation is a key strategy for restoring ecosystems in post-mining areas (Parikh *et al.* 2021). The presence of insects within a region can serve as an indicator of biodiversity, ecosystem health, and landscape degradation. The government plays a crucial role in overseeing and enforcing post-mining regulations to ensure compliance with established standards. Semen Tonasa, a major cement producer in Eastern Indonesia, utilises limestone and clay as key raw materials in its production processes (Lengke *et al.* 2023). Effective land management is crucial to preventing environmental degradation.

Post-mining research faces challenges due to low soil fertility and altered ecosystems resulting from past mining (Padhiary & Kumar 2024). Mining activities can cause ecological damage, ranging from ecosystem changes to habitat destruction for organisms. In limestone areas, structurally degraded soils alter microclimatic conditions, which directly impact the survival of ground-dwelling insects (Hodecek *et al.* 2016). A similar situation is observed in clay mining areas, where dense soil structures and low air content further limit the diversity and adaptability of insect species. Reclamation should consider the adaptability of insects to altered conditions (Brusseau *et al.* 2019).

This study introduces a microclimatic approach to understanding how ground-dwelling insects interact with and adapt to reclaimed post-mining areas. This study provides novel insights into insect species that can survive in heavily degraded ecosystems by analysing factors such as air temperature, humidity, light intensity, wind speed, soil pH, and soil temperature at the research site. Identifying insect species with high adaptability to extreme conditions could indicate the success of reclamation processes and overall ecosystem recovery. The present study aims to analyse the relationship between microclimate and the diversity of ground-dwelling insects in limestone and clay mining areas that have been reclaimed over different reclamation periods. The novelty of this study lies in its simultaneous examination of ground-dwelling insect functionality, their correlation with microclimatic factors, and

comparative ecological trajectories between two distinct substrates, limestone and clay, representing different stages of post-mining land reclamation. The study also provides insights into sustainable reclamation efforts and is a scientific foundation to strengthen climate change mitigation through enhanced soil ecosystem quality.

## 2. Materials and Methods

### 2.1. Study Location

This research took place from May to October 2024. This research was carried out on reclaimed land in the former mining area of PT Semen Tonasa, Pangkep Regency, South Sulawesi, Indonesia. PT Semen Tonasa is a mining company based in Pangkep Regency, with a mining area located in the Biring Ere Karst area. PT Semen Tonasa has a land area of 1,571 hectares. Based on its geographical location, PT Semen Tonasa is located at 04°79'96"-04°78'34" South Latitude and 119°60'85"-119°61'61 East Longitude (Figure 1). The limestone mining area is 50-200 m asl, and the clay mines are at an altitude of 10-100 m asl.

Limestone reclamation is located in karst formations around the factory complex and the limestone mining exploitation area. The land's surface consists of complex, critical rock and is not fertile. The former limestone mining land is planted with plants endemic to Sulawesi that have high economic value, namely *Vitex Cofassus*. Apart from that, there are several other types, such as *Mimusops elengi* and *Swietenia mahagoni*. In the reclamation of ex-limestone mining areas, research was conducted in three locations based on different reclamation ages: the 2012 ex-mining reclamation, covering an area of 1 ha; the 2018 ex-mining reclamation, covering an area of 1.07 ha; and the 2023 ex-mining reclamation, covering an area of 0.49 ha. The research location is situated at an altitude of 77.5-97 m above sea level (asl). The ground-dwelling conditions are challenging because of the embankment above the natural karst.

The former clay mining land was reclaimed to become the Bulu Sipong Biodiversity Park (Kehati) in Bulusipong Village, Biring Ere Village, Bungoro District, Pangkep Regency. Biodiversity Park is one of the conservation efforts aimed at preserving biodiversity and restoring the surrounding environment. The research location is a karst area with a rich ecosystem that is of great importance to protect. In clay reclamation, research was conducted in three locations based on different reclamation ages: ex-mining reclamation in 2017, covering an area of 2.18 ha; ex-mining reclamation in 2020, covering an area of

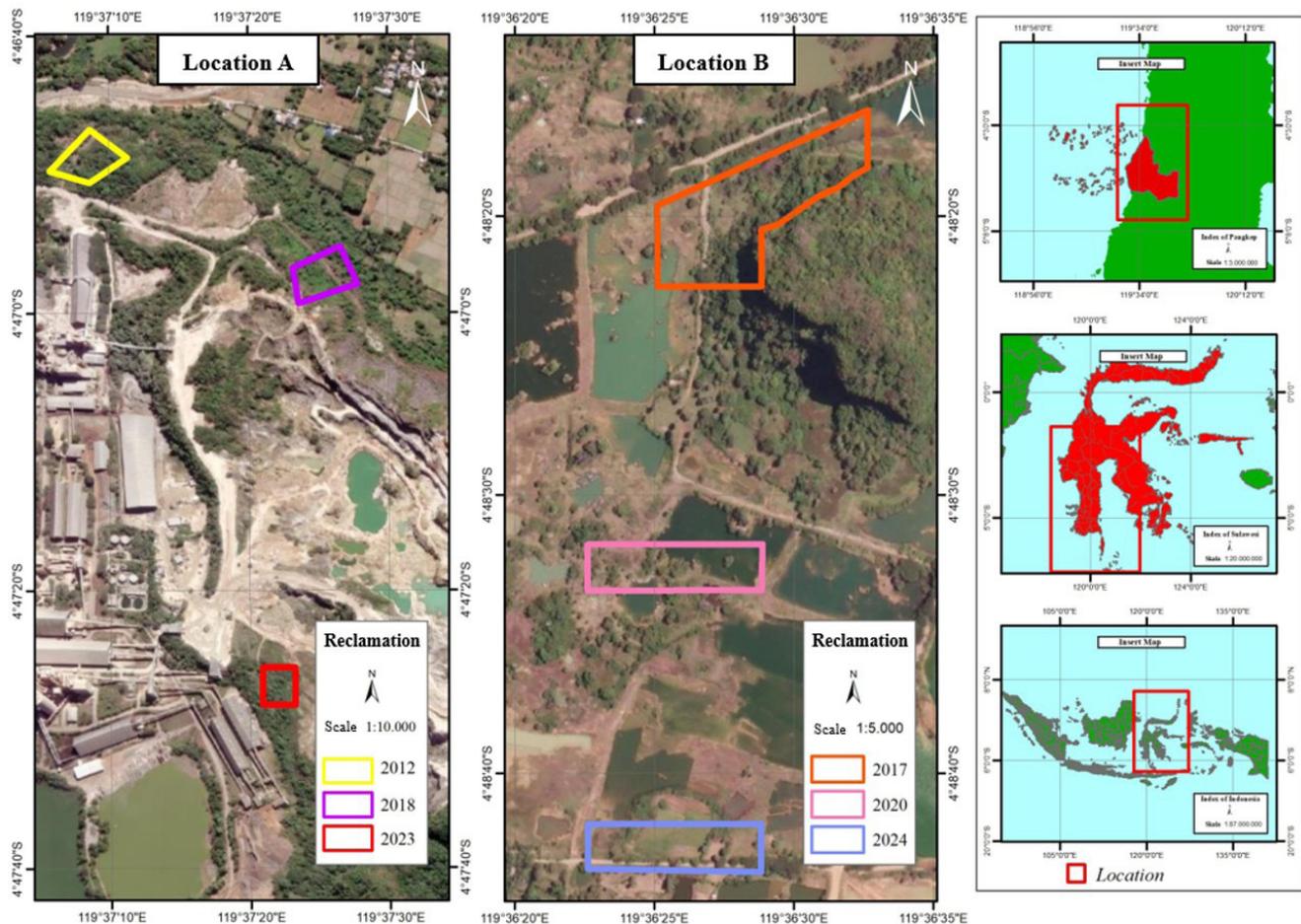


Figure 1. Research location map. (A) Limestone mine reclaimed land and (B) clay mine reclaimed land

0.98 ha; and ex-mining reclamation in 2024, covering an area of 0.98 ha. In 2017, the reclaimed land was used as a nature reserve. The types of plants planted at this reclamation location are *Albizia chinensis*, *Mimusops elengi*, *Lannea coromandelicas*, and *Delonix regia*. This location is situated at an altitude of 50 m above sea level (asl).

## 2.2. Data Collecting

Sampling was conducted on reclaimed land in former limestone and clay mining areas to determine the diversity of ground-dwelling insects in two types of areas and at different ages of reclamation. Sampling was conducted once a month, three times a month. The data collection technique to be employed utilises the pitfall trap method. Each reclaimed land has four plots consisting of three trap points. Pitfall traps made from plastic cups have a diameter of 5.3 cm and a height of 9.5 cm. Plastic cups are embedded into the soil and will be filled with 70% alcohol to collect trapped insects. The

top of the pitfall trap will be covered with Styrofoam to prevent rainwater, leaves, twigs, or falling objects. The research will be conducted on three reclaimed lands of varying ages, resulting in three classes of reclamation, each with distinct ecosystems and a diverse array of insect types.

Measurement of environmental factors consists of temperature ( $^{\circ}\text{C}$ ), air humidity (%), light intensity (lux), wind speed (m/s), soil pH, and soil temperature ( $^{\circ}\text{C}$ ). Measurement of environmental (Table 1) factors at each observation location in the morning (07:00-09:00), noon (11:00-13:00), and afternoon (15:00-17:00). Measurements were carried out during the research period. The data will be tabulated, averaged, and then analysed with other variables.

## 2.3. Insect Identification

Ground-dwelling insects obtained and collected will be identified to determine their type and the number of individuals of each species. Each species will be

Table 1. Index of diversity, abundance, evenness, and dominance, with climatic conditions on limestone and clay reclaimed land

Location	Year	T	H	X	S	pH	Ts
Limestone reclamation	2012	33.5	61.6	3125.7	0.6	6.9	31.5
	2018	32.2	66.9	3027.3	1.0	7.0	30.7
	2023	37.3	55.7	3501.3	1.3	6.9	35.0
Clay reclamation	2017	31.8	66.6	2741	0.4	6.9	29.0
	2020	37.9	53.8	3405.3	1.0	7.3	33.3
	2024	36.8	56.5	3288.7	1.0	6.5	33.4

(H') diversity, (Dmg) abundance, (E) evenness, (D) dominance, (T) air temperature, (H) humidity, (X) light intensity, (S) wind speed, (pH) soil pH, and (Ts) soil temperature

observed using a stereo microscope (Stem 2000 with an Erc 5S phototube camera) to measure and take pictures. The samples will then be identified using insect identification keys based on available literature, supported by reference images and species distribution data from the iNaturalist website. This combination of morphological analysis and digital resources helps ensure accurate identification and classification.

## 2.4. Data Analysis

Data analysis was carried out using the Shannon-Wiener diversity index (H'), richness index (R), evenness index (E), and dominance index (D) (Kahirun *et al.* 2023). Next, correlation analysis and principal component analysis (PCA) will be performed in XLSTAT to analyse the correlation or influence of climate on insect distribution. This analysis aims to determine how various microclimate factors, such as temperature, humidity, light intensity, soil pH, and soil temperature, correlate with the composition of soil-dwelling insects. The results will provide insight into which environmental variables most influence insect communities and can serve as ecological indicators to evaluate the success of land reclamation efforts.

## 3. Results

### 3.1. Ground-Dwelling Insect Composition on Reclaimed Land

A total of 36 species of ground-dwelling insects from various orders were successfully trapped in both limestone and clay reclamation sites, with their distribution varying according to the year of reclamation (Table 2). Species from the Formicidae family (Hymenoptera), such as *Iridomyrmex anceps*, *Carebara diversa*, and *Dolichoderus thoracicus*, were recorded across all reclamation years in both limestone and clay sites, indicating strong ecological resilience and high adaptability of the ant species to habitat changes. Other species, such as *Oecophylla*

*smaragdina*, *Camponotus irritans*, and *Pheidole megacephala*, were found exclusively in clay reclamation sites, suggesting a preference for specific habitat types. Conversely, species from the order Coleoptera, such as *Monocrepidius exsul* (Elateridae) and *Anthicus melancholicus* (Anthicidae), showed more limited distributions, appearing only during specific periods and only in limestone areas, reflecting more specialised habitat requirements. The Orthoptera group, including *Atractomorpha crenulata*, *Oxya japonica*, and *Phaneroptera falcata*, was observed only at specific locations and reclamation years, which may indicate sensitivity to vegetation dynamics. Other orders, such as Diptera, Dermaptera, and Blattodea, contributed only one or two species each, including *Dermatobia hominis*, *Euborellia annulipes*, and *Blattella germanica*, highlighting the diverse potential for ecological succession across these reclaimed habitats.

The composition of trapped ground-dwelling insects from reclaimed mining sites in South Sulawesi further emphasises the dominance of a few adaptive species (Figure 2). *D. thoracicus* was by far the most abundant species, with a total of 19,372 individuals, followed by *C. diversa* with 2,442 individuals and *A. gracilipes* with 637 individuals. These three ant species alone accounted for over 90% of all individuals recorded, highlighting their ecological resilience and capacity to thrive in post-mining environments. Other relatively abundant species included *I. anceps* (244 individuals), *P. megacephala* (191), and *C. pennsylvanicus* (72), all of which belong to the Formicidae family, reinforcing the pattern of ant dominance in these disturbed ecosystems. Moderate abundances were also observed in species such as *B. germanica* (67), *P. fervens* (49), and *T. vitiensis* (50), suggesting their potential role in early successional stages of habitat recovery. In contrast, many species were recorded in very low numbers, with 20 species represented by fewer than 10 individuals, such as *P. hesperus*, *D. hominis*,

Table 2. Distribution of trapped ground-dwelling insects in limestone and clay reclamation sites

Order	Family	Species	Limestone reclamation year			Clay reclamation year		
			2012	2018	2023	2017	2020	2024
Hymenoptera	Formicidae	<i>Iridomyrmex anceps</i> Roger (1863)	+	+	+	+	+	+
		<i>Carebara diversa</i> Jerdon (1851)	+	+	+	+	+	+
		<i>Pheidole fervens</i> Smith (1858)	+	+	-	+	-	+
		<i>Dolichoderus thoracicus</i> Smith F. (1860)	+	+	+	+	+	+
		<i>Technomyrmex vitiensis</i> Mann (1921)	+	+	+	-	+	+
		<i>Camponotus pennsylvanicus</i> De Geer (1773)	+	-	+	+	+	+
		<i>Anoplolepis gracilipes</i> Smith F. (1857)	-	+	+	-	+	-
		<i>Odontoponera</i> sp.	-	+	+	+	-	-
		<i>Oecophylla smaragdina</i> Fabricius (1775)	-	-	-	+	-	-
		<i>Camponotus irritans</i> Smith F. (1857)	-	-	-	+	-	-
Hymenoptera	Eulophidae	<i>Pheidole megacephala</i> Fabricius (1793)	-	-	-	+	-	+
		<i>Diglyphus</i> sp.	+	-	-	-	-	-
Coleoptera	Elateriadae	<i>Monocrepidius exsul</i> Sharp (1877)	-	+	-	-	-	-
	Chrysomelidae	<i>Longitarsus jacobaeae</i> Waterhouse (1858)	-	+	-	-	-	-
	Anthicidae	<i>Anthicus melancholicus</i> Oustalet (1874)	-	+	+	-	-	-
	Carabidae	<i>Anisodactylus nigrita</i> Dejean (1829)	-	-	-	+	-	-
	Cantharidae	<i>Chauliognathus</i> sp.	-	+	-	-	-	-
	Trogidae	<i>Omorgus costatus</i> Wiedemann (1823)	-	-	-	-	+	-
	Scarabaeidae	<i>Canthon viridis</i> Palisot de Beauvois (1805)	-	-	-	-	-	+
	Endomychidae	<i>Endomychus biguttatus</i> Say (1824)	-	-	-	-	-	+
Orthoptera	Acrididae	<i>Valanga nigricornis</i> Burmeister (1838)	+	-	+	+	-	-
	Trigonidiidae	<i>Dianemobius fascipes</i> Walker (1869)	+	+	+	-	+	+
	Gryllidae	<i>Gryllus assimilis</i> Fabricius (1775)	-	-	+	+	+	+
	Tetrigidae	<i>Tetrix subulata</i> Linnaeus (1761)	+	+	+	-	-	-
	Trigonidiidae	<i>Eunemobius carolinus</i> Scudder (1877)	+	-	+	+	+	+
	Pyrgomorphidae	<i>Atractomorpha crenulata</i> Fabricius (1793)	-	-	-	+	-	-
	Acrididae	<i>Oxya japonica</i> Thunberg (1815)	-	-	-	+	-	-
	Tettigoniidae	<i>Phaneroptera falcata</i> Poda (1761)	-	-	-	+	-	-
Hemiptera	Cicadellidae	<i>Orosius orientalis</i> Matsumura (1914)	+	-	+	-	+	+
	Cicadellidae	<i>Evacanthus acuminatus</i> Fabricius (1794)	-	-	+	-	+	-
Blattodea	Ectobiidae	<i>Lobopterella dimidiatipes</i> Bolívar (1890)	+	-	+	-	-	-
	Ectobiidae	<i>Blattella germanica</i> Linnaeus (1767)	+	+	+	-	-	+
Dermaptera	Anisolabididae	<i>Euborellia annulipes</i> H. Lucas (1847)	-	+	-	-	-	-
Mantodea	Miomantidae	<i>Miomantis caffra</i> Saussure (1871)	-	-	-	+	-	-
Diptera	Oestridae	<i>Dermatobia hominis</i> Linnaeus Jr. (1781)	-	-	-	+	-	-
Phasmatodea	Heteronemiidae	<i>Parabacillus hesperus</i> Hebard (1934)	-	-	-	-	-	+

The plus (+) and minus (-) signs indicate the presence or absence of each insect species across different reclamation years or sites

*M. caffra*, and *E. biguttatus*, indicating either rare occurrence or specialised habitat requirements that are not fully met in the reclamation areas. This disparity in individual counts reflects an uneven distribution of insect biodiversity in reclaimed landscapes, where a few dominant species may outcompete others, shape community composition, and potentially influence ecological functions during the restoration process.

### 3.2. Roles of Trapped Ground-Dwelling Insects

The diverse roles of ground-dwelling insects trapped in reclaimed limestone and clay mine sites

reveal their significant ecological functions in post-mining environments (Table 3). Most dominant species belong to the family Formicidae (Hymenoptera), which serve multifaceted roles as foragers, decomposers, bioindicators, and biological control agents. For instance, *I. anceps* and *C. diversa* function both as decomposers and foragers, while *P. fervens* and *C. pennsylvanicus* are additionally recognized as scavengers and biological control agents, respectively. *D. thoracicus* is known for its predatory role, and species like *T. vitiensis* and *Odontoponera* sp. contribute to biological pest control. *O. smaragdina*

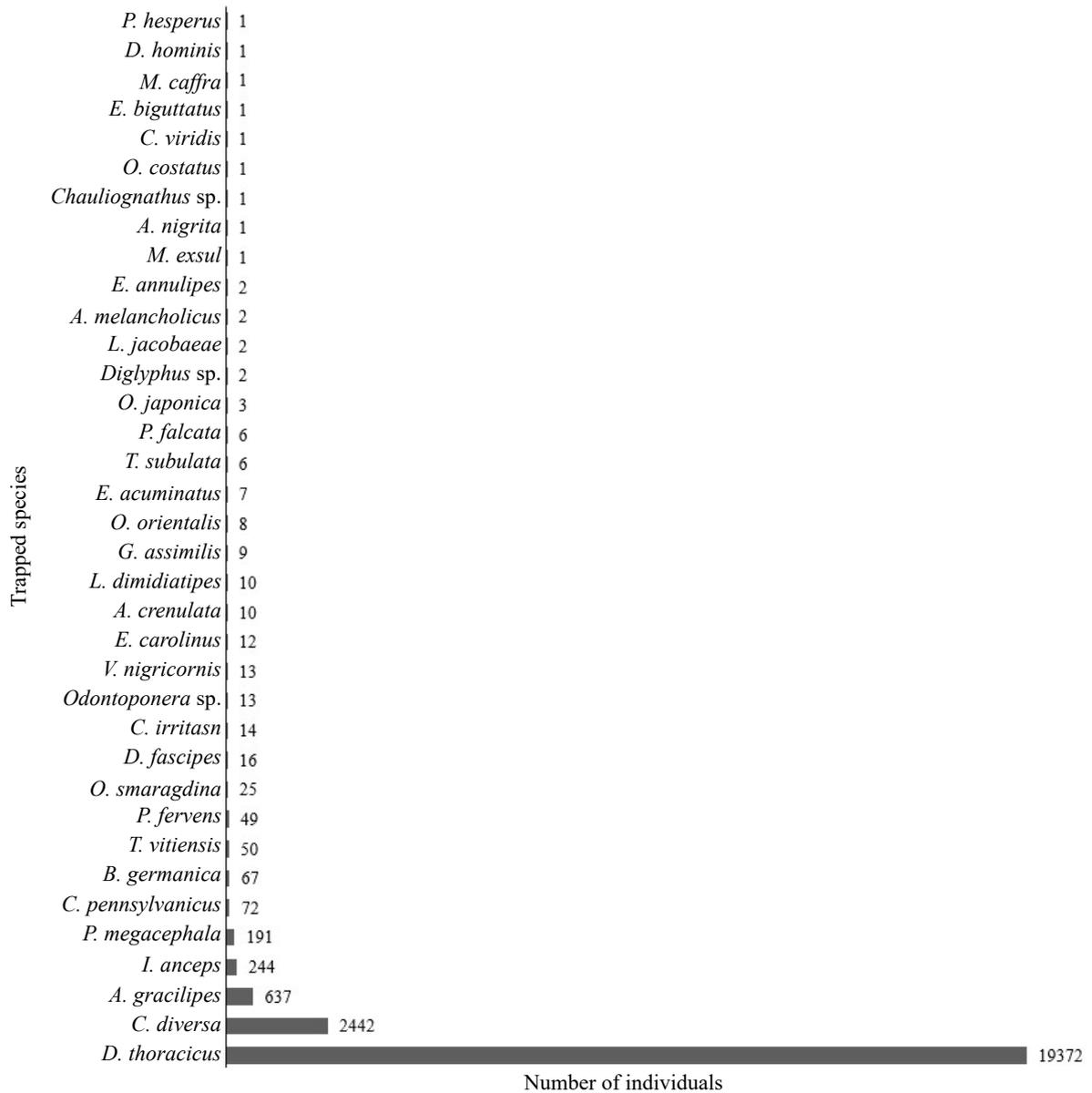


Figure 2. The abundance of trapped ground-dwelling insects in limestone and clay reclamation

Table 3. Roles of trapped ground-dwelling insects in reclaimed limestone and clay sites

Order	Family	Species	Roles
Hymenoptera	Formicidae	<i>I. anceps</i>	Foragers, bioindicators, and decomposers (Lu <i>et al.</i> 2016; Zhou <i>et al.</i> 2023)
		<i>C. diversa</i>	Foragers and decomposers (Singh <i>et al.</i> 2020; Wanna <i>et al.</i> 2022)
		<i>P. fervens</i>	Foragers, bioindicators, and scavengers (Dai 2022; Budi Aman <i>et al.</i> 2025)
		<i>D. thoracicus</i>	Foragers and predators (Abdullah <i>et al.</i> 2020; Johari <i>et al.</i> 2021)
		<i>T. vitiensis</i>	Foragers
		<i>C. pennsylvanicus</i>	Foragers and biological control agents (Gracia 2017; Crist <i>et al.</i> 2017)
		<i>A. gracilipes</i>	Foragers and predators (Lee & Yang 2022; Abdullah <i>et al.</i> 2024)
		<i>Odontoponera</i> sp.	Foragers and biological control agents (Rahardjo <i>et al.</i> 2023)
		<i>O. smaragdina</i>	Foragers, predators, and biological control agents (Exélis <i>et al.</i> 2022)
		<i>C. irritans</i>	Foragers and biological control agents (Tuma <i>et al.</i> 2020)
		<i>P. megacephala</i>	Foragers, predators, and decomposers (Milligan <i>et al.</i> 2016; Ogogol <i>et al.</i> 2017)
		Eulophidae	<i>Diglyphus</i> sp.

Table 3. Continued

Order	Family	Species	Roles
	Elateriidae	<i>M. exsul</i>	Foragers
	Chrysomelidae	<i>L. jacobaeae</i>	Foragers (Govorun 2023)
	Anthicidae	<i>A. melancholicus</i>	Foragers
	Carabidae	<i>A. nigrita</i>	Foragers and bioindicators (Gokturk & Celik 2017; Aleksanov <i>et al.</i> 2023)
	Cantharidae	<i>Chauliognathus</i> sp.	Foragers and bioindicators (Weiherer <i>et al.</i> 2020; Elmquist <i>et al.</i> 2022)
	Trogidae	<i>O. costatus</i>	Foragers
	Scarabaeidae	<i>C. viridis</i>	Foragers and bioindicators (Shah <i>et al.</i> 2021; Kim <i>et al.</i> 2024)
	Endomychidae	<i>E. biguttatus</i>	Foragers
Orthoptera	Acrididae	<i>V. nigricornis</i>	Foragers and biological control agents (Perdhana 2023)
	Trigonidiidae	<i>D. fascipes</i>	Foragers
	Gryllidae	<i>G. assimilis</i>	Foragers and bioindicators (Merugu & Narayana 2024)
	Tetrigidae	<i>T. subulata</i>	Foragers and bioindicators (Walcher <i>et al.</i> 2022)
	Trigonidiidae	<i>E. carolinus</i>	Foragers
	Pyrgomorphidae	<i>A. crenulata</i>	Foragers and bioindicators (Leksono <i>et al.</i> 2024)
	Acrididae	<i>O. japonica</i>	Foragers and predators (Hayasshi 2023)
	Tettigoniidae	<i>P. falcata</i>	Foragers and bioindicators (Dvorak <i>et al.</i> 2022)
Hemiptera	Cicadellidae	<i>O. orientalis</i>	Foragers (Sonmez & Ozgen 2025)
	Cicadellidae	<i>E. acuminatus</i>	Foragers
Blattodea	Ectobiidae	<i>L. dimidiatipes</i>	Foragers
	Ectobiidae	<i>B. germanica</i>	Foragers (Ko <i>et al.</i> 2017)
Dermaptera	Anisolabididae	<i>E. annulipes</i>	Foragers (Trumbo 2018)
Mantodea	Miomantidae	<i>M. caffra</i>	Foragers and bioindicators (Soliman & El-Shazly 2017)
Diptera	Oestridae	<i>D. hominis</i>	Foragers (Galetti <i>et al.</i> 2018)
Phasmatodea	Heteronemiidae	<i>P. hesperus</i>	Foragers

and *P. megacephala* exemplify multifunctional insects, acting as foragers, predators, and decomposers, which support the regeneration of soil health and plant communities. Beyond ants, species from the *Coleoptera* order, such as *M. exsul* (Elateridae) and *A. nigrita* (Carabidae), play essential roles as foragers and bioindicators. At the same time, *Chauliognathus* sp. (Cantharidae) also contributes to biological control. Members of Orthoptera, such as *V. nigricornis*, *T. subulata*, and *P. falcata*, serve as both foragers and bioindicators, reflecting changes in vegetation and habitat quality. Other insect orders also contribute meaningfully. *O. orientalis* (Hemiptera: Cicadellidae) acts as a forager, while *B. germanica* (Blattodea), *D. hominis* (Diptera), and *M. caffra* (Mantodea) function as foragers or occasional predators. The presence of *Diglyphus* sp. (Eulophidae), a recognised biological control agent, and the decomposer *E. annulipes* (Dermaptera), highlights the trophic complexity and functional diversity of insect communities in reclaimed lands. These roles underscore the critical contribution of ground-dwelling insects not only to sustaining ecological processes but also to signalling the progress and effectiveness of ecological restoration in post-mining environments. Several representative insect species identified during the survey (Figure 3) belong

to ecologically significant taxa, such as predatory ants (*O. smaragdina*) and saprophagous beetles (*C. viridis*), each contributing to the assessment of habitat recovery on reclaimed post-mining land.

### 3.3. Diversity, Richness, Evenness, and Dominance of Ground-Dwelling Insects

The diversity index shows varying values on reclaimed land from former limestone and clay mines in Pangkep Regency (Figure 4). On reclaimed limestone mine land, the highest diversity value was achieved in 2023 with an index of 1.92, while the lowest value was in 2012 at 0.17. Meanwhile, the clay mine reclaimed land showed the highest diversity value in 2017, at 3.32, indicating that clay mine reclamation supports better insect diversity compared to limestone mines during a specific period. The richness index, which reflects the number of species, peaked in the 2017 clay mine reclamation area with a value of 3.32, indicating a significantly higher species count compared to other years and sites, particularly limestone mine reclamations, which reached only 1.92 in 2023. The uniformity index indicates a more uniform level of species distribution on reclaimed land from clay mines compared to limestone mines. In 2024, the evenness value for clay mines is expected to be 1.12, while for

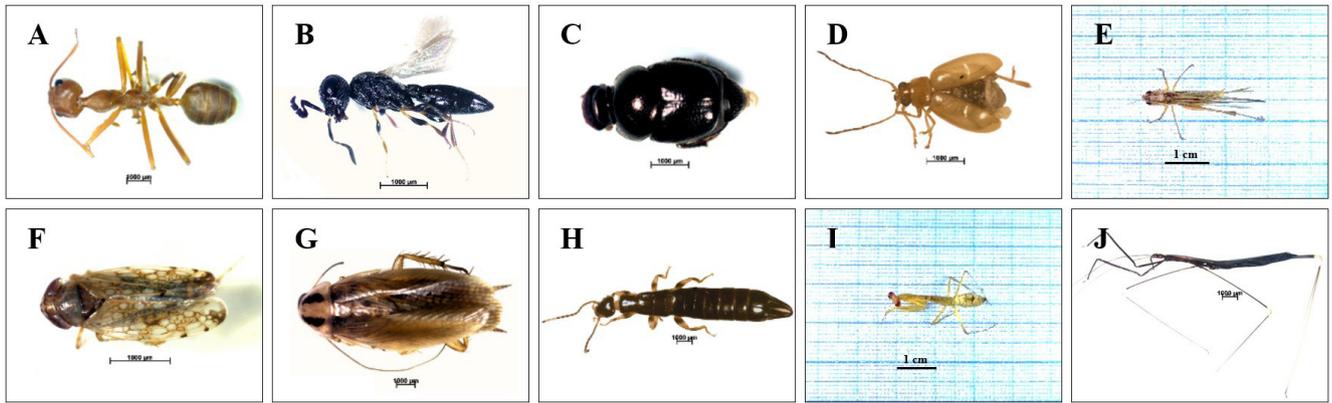


Figure 3. Representative insect species recorded in the study area. (A) *Oecophylla smaragdina*, (B) *Diglyphus* sp., (C) *Canthon viridis*, (D) *Longitarsus jacobaeae*, (E) *Oxya japonica*, (F) *Orosius orientalis*, (G) *Blattella germanica*, (H) *Euborellia annulipes*, (I) *Miomantis caffra*, (J) *Parabacillus hesperus*

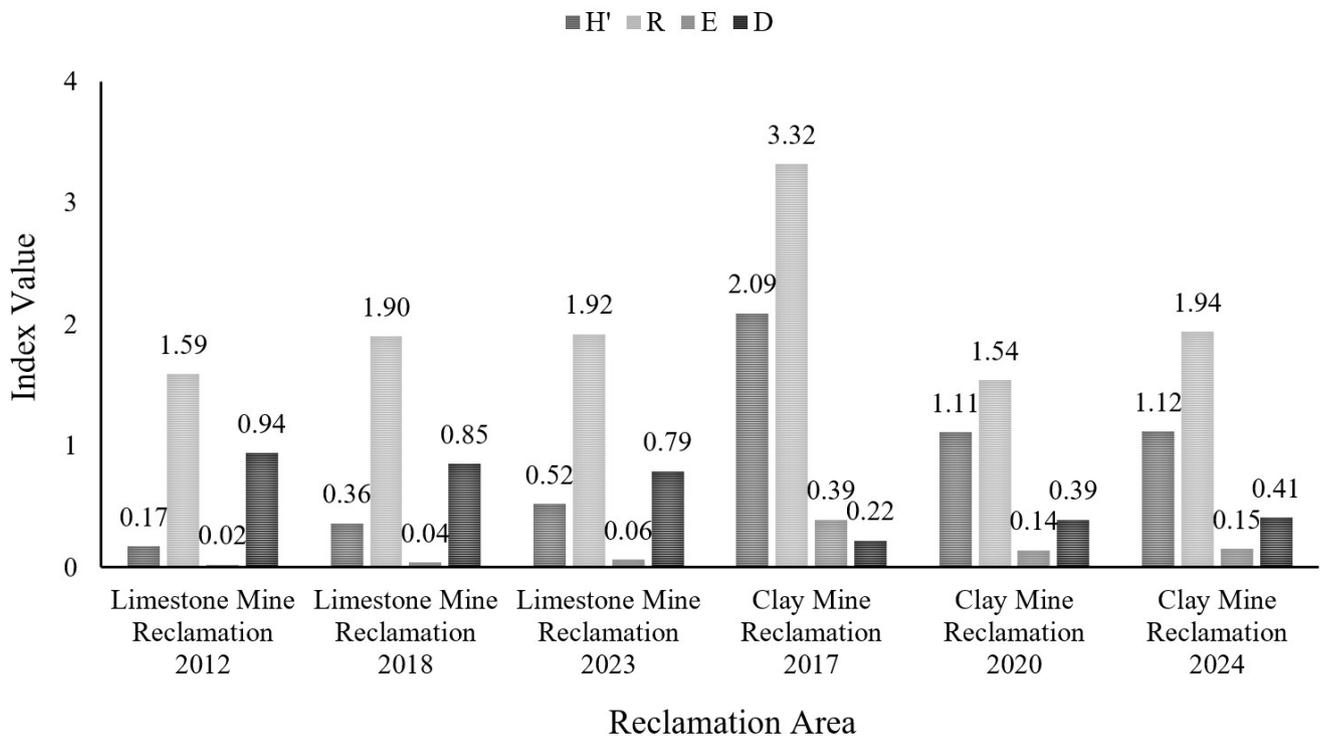


Figure 4. Index values for diversity, richness, evenness, and dominance of insects on reclaimed land for limestone and clay mines

limestone mines, it will only reach 0.79 in 2023. The distribution of ground-dwelling insect populations in clay mines is more even. Meanwhile, the dominance index shows a trend of higher dominance of particular species in limestone mines compared to clay mines. The highest dominance value in a limestone mine was recorded at 0.52 in 2018, indicating the presence of a particular dominant species.

### 3.4. Correlation of Insect Distribution with Climate

In limestone mines, diversity values tend to increase from 2012 to 2023 (0.17 to 0.52), along with an increase in soil temperature from 31.5 to 35°C. In contrast, in clay mines, the highest H' value was recorded in 2017 (2.09) and decreased in 2024 (1.12), which could be attributed to fluctuations in light intensity and soil pH.

Humidity conditions and air temperature also have an important role in determining the ground-dwelling insect diversity index. In clay mines, higher humidity (66.6%) in 2017 was directly proportional to the high diversity value (2.09). Meanwhile, dominance in limestone mines decreased over time (from 0.94 in 2012 to 0.79 in 2023), indicating reduced dominance of particular species and increased ecosystem stability.

A significant positive relationship (Table 4) between diversity and richness ( $r = 0.80$ ) and uniformity ( $r = 0.98$ ), indicating that diversity increases with higher richness and an even distribution of species. In contrast,

diversity had a negative correlation with dominance ( $r = -0.95$ ), indicating that high diversity is typically associated with low dominance. Soil temperature and light intensity had a significant correlation with the diversity index ( $r = -0.40$  and  $-0.46$ ), indicating the influence of physical factors on the composition of ground-dwelling insects. Additionally, humidity showed a positive correlation with diversity, suggesting that optimal microhabitat conditions foster ground-dwelling insect diversity.

The results of the PCA analysis (Figures 5, 6, and 7) show the grouping pattern of environmental

Table 4. Results of the correlation between insect diversity and climate on limestone and clay reclaimed land

	H'	R	E	D	T	H	X	S	pH	Ts
H'	1									
R	0.80**	1								
E	0.98**	0.89**	1							
D	-0.95**	-0.59	-0.88**	1						
T	-0.11	-0.55	-0.27	-0.13	1					
H	0.13	0.58	0.28	0.11	-0.99**	1				
Lux	-0.46	-0.75*	-0.59	0.25	0.93**	-0.91**	1			
S	-0.47	-0.59	-0.59	0.31	0.71*	-0.62*	0.85**	1		
pH	-0.06	-0.21	-0.08	0.04	0.05	-0.06	0.09	0.03	1	
Ts	-0.40	-0.65*	-0.53	0.21	0.92**	-0.90**	0.98**	0.85**	-0.07	1

(H') diversity, (R) richness, (E) evenness, (D) dominance, (T) air temperature, (H) humidity, (X) light intensity, (S) wind speed, (pH) soil pH, and (Ts) soil temperature

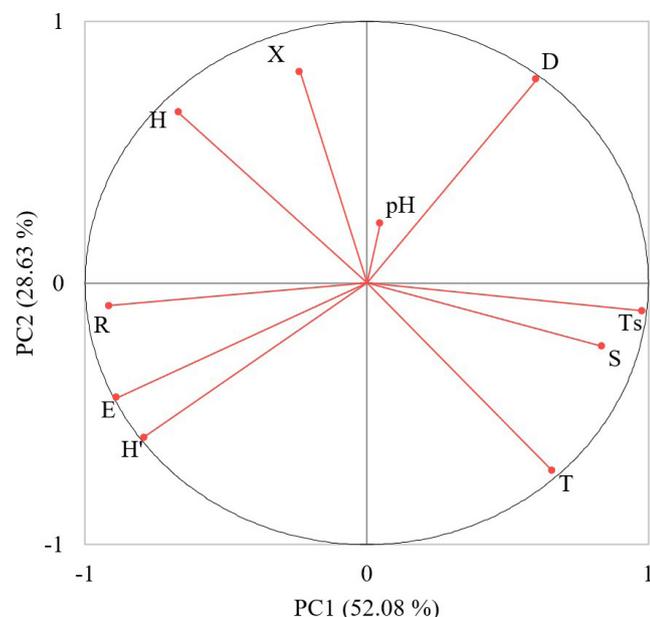


Figure 5. PCA results of the relationship between microclimate and ground-dwelling insect diversity on reclaimed limestone and clay mines. (H') diversity, (R) richness, (E) evenness, (D) dominance, (T) air temperature, (H) humidity, (X) light intensity, (S) wind speed, (pH) soil pH, and (Ts) soil temperature

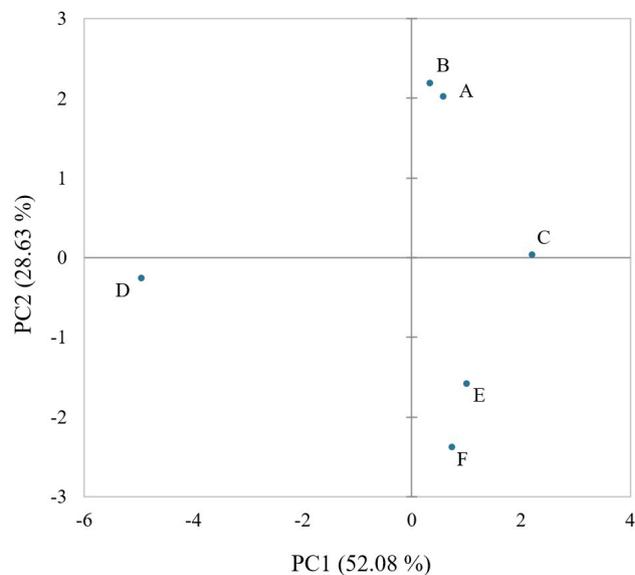


Figure 6. PCA results of the correlation between the proximity of reclaimed land for limestone and clay mines. Limestone mine reclamation, (A) 2012, (B) 2018, and (C) 2023. Clay mine reclamation, (D) 2017, (E) 2020, and (F) 2024

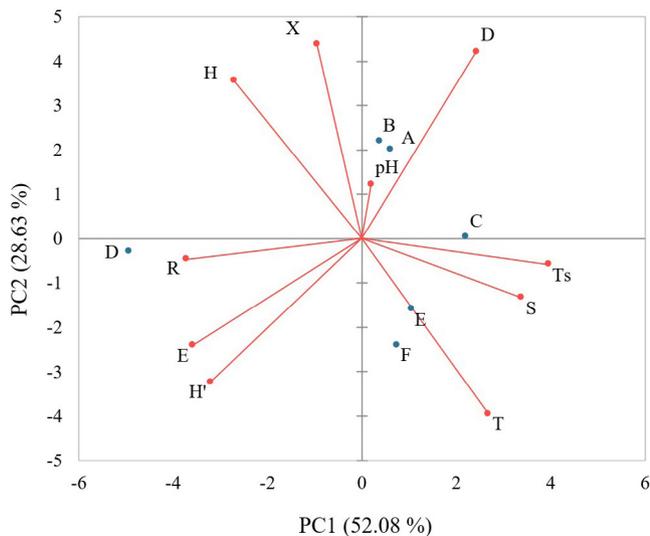


Figure 7. Biplot PCA of variable clustering. Limestone mine reclamation, (A) 2012, (B) 2018, and (C) 2023. Clay mine reclamation, (D) 2017, (E) 2020, and (F) 2024. (H') diversity, (R) richness, (E) evenness, (D) dominance, (T) air temperature, (H) humidity, (X) light intensity, (S) wind speed, (pH) soil pH, and (Ts) soil temperature

variables and insect diversity indices on the reclaimed limestone and clay mines. The PC1 axis accounts for 52.08% of the data variation, while PC2 accounts for 28.63%, indicating that these two main components collectively cover 80.71% of the total data variability. Environmental variables, such as air temperature, humidity, light intensity, wind speed, soil pH, and soil temperature, have vectors that illustrate their contributions to differences in conditions between reclamation locations. Air temperature and soil temperature have a high positive correlation with PC1, indicating that these two factors play a significant role in the differences in characteristics between reclamation locations. The grouping of reclamation years reveals that the limestone mine sites in 2012, 2018, and 2023 exhibit distinct characteristics compared to the clay reclamation sites in 2017, 2020, and 2024. The clay reclamation site in 2017 had a high dominance index, whereas the clay reclamation site in 2020 exhibited lower diversity and evenness values.

#### 4. Discussion

The success of post-mining land restoration depends on the ability to recreate a balanced ecosystem and support local biodiversity. Analysis of ground-dwelling insect diversity revealed that reclamation had a significant influence on community structure (Buchori *et al.* 2018). In limestone mining, low

diversity index values in the early stages of reclamation indicate environmental conditions that do not support species diversity. Over a decade of reclamation has shown an increase in diversity, especially in clay mining areas, where decomposers and foragers such as *G. assimilis* (Gryllidae) and *T. subulata* (Tettigoniidae) are frequently recorded and serve as key indicators of restoration success (Goncalves *et al.* 2021; Walcher *et al.* 2022). Increased insect diversity is supported by effective microclimate management, improved soil moisture, and reduced extreme light intensity (De Frenne *et al.* 2021). Successful reclamation has also contributed to a rise in ground-dwelling insect diversity over time (Juwarkar *et al.* 2016), where climate factors play a role in shaping insect communities in disturbed ecosystems (Cours *et al.* 2023).

Species of the Formicidae family (ants) play roles in the restoration of degraded ecosystems (Triyogo *et al.* 2020; Roy and Singh 2024). Notably, *D. thoracicus*, found dominantly in both clay and limestone sites, serves as both a forager and predator (Abdullah *et al.* 2020; Johari *et al.* 2021), promoting natural pest control and balancing trophic levels. Species such as *I. anceps* and *C. diversa* function as foragers and decomposers (Lu *et al.* 2016; Singh *et al.* 2020; Zhou *et al.* 2023), contributing to soil turnover and nutrient recycling. The dominance of *A. gracilipes* and *P. megacephala* in the clay site in 2024, with 637 and 191 individuals, respectively, demonstrates their adaptive success in restored ecosystems. These ants not only act as foragers and decomposers but also as predators, underscoring their multifunctionality (Milligan *et al.* 2016; Lee & Yang 2022). Meanwhile, *T. vitiensis*, with moderate population levels, acts as a forager and may serve as a subtle indicator of improving soil quality (Crist *et al.* 2017). Their presence is a promising sign of habitat suitability and gradual ecological succession. Other ants, such as *C. pennsylvanicus* and *C. irritans*, play roles in biological control, reflecting the potential of these species in integrated pest management during early succession stages (Gracia 2017; Tuma *et al.* 2020).

Beyond ants, a broad range of insect taxa contribute to the ecological resilience of reclaimed land, demonstrating varied functional roles tied to their order and family. Species from the order Coleoptera, such as *A. nigrita* (Carabidae) and *Chauliognathus* sp. (Cantharidae), act as foragers and bioindicators, showing sensitivity to habitat changes and progress in restoration (Weiherer *et al.* 2020; Aleksanov *et al.*

2023). The consistent presence of *M. exsul* (Elateridae) and *L. succineus* (Chrysomelidae) further supports their role as foragers in soil recovery processes (Govorun 2023). Orthoptera species like *V. nigricornis* function as foragers and biological control agents through vegetation feeding (Perdhana 2023). The existence of *P. crenulata* and *P. falcata* as foragers and bioindicators in disturbed areas highlights their utility in monitoring soil and vegetation restoration (Dvorak *et al.* 2022; Leksono *et al.* 2024). Blattodea (*B. germanica*) and Dermaptera (*E. annulipes*) contribute as decomposers, breaking down organic matter and accelerating nutrient cycling (Ko *et al.* 2017; Trumbo 2018). The presence of *Diglyphus* sp. (Eulophidae) confirms the functioning of a biological control dynamic in reclaimed ecosystems (Wan-Xue 2018), while predatory species such as *O. japonica* and *M. caffra* signal trophic maturity in advanced succession stages (Hayashi 2023). The combination of these ecological roles—foraging, decomposition, and predation—provides crucial insight into ecosystem recovery dynamics. The presence of such functional diversity aligns with the principle that a well-functioning ecosystem is not only species-rich but also composed of organisms fulfilling essential ecosystem services (Alexander *et al.* 2016; Budiaman *et al.* 2025). Therefore, these insects are indispensable as bioindicators and agents of ecosystem engineering in post-mining restoration frameworks in Indonesia.

Ground-dwelling insect diversity reflects the success and trajectory of ecosystem recovery in reclaimed mining areas. Across both limestone and clay mine reclamation sites in Pangkep Regency, a discernible trend of increasing diversity over time is evident. Limestone mines demonstrated gradual improvement, with the Shannon-Wiener index rising from 0.17 in 2012 to 1.92 in 2023, while clay mines reached a peak of 3.32 in 2017. The evenness index was also higher on clay sites, suggesting a more balanced distribution of individuals among species. These trends indicate that reclamation on clay substrates, potentially due to their superior water retention, high organic matter content, and regrowth of vegetation, supports a more resilient and heterogeneous ground-dwelling insect community (Lu *et al.* 2021). Dominance values remained higher in limestone areas, with a value of 0.52 recorded in 2018, indicating that some habitats continue to be dominated by a few species. Such imbalances reflect slower or incomplete ecological restoration processes, where competitive exclusion still occurs due to limited resources or microhabitat variability (Budiaman *et al.* 2025).

Environmental variables have a significant impact on insect diversity and distribution in reclaimed mining areas. Humidity, for instance, demonstrated a positive correlation with diversity, particularly in 2017, when a humidity level of 66.6% coincided with the highest diversity value on clay sites. Conversely, both soil temperature and light intensity showed moderate negative correlations with diversity ( $r = -0.40$  and  $-0.46$ ), which aligns with previous studies that found excessive light and heat to be stressors for ground-dwelling organisms (De Frenne *et al.* 2021; Cours *et al.* 2023). PCA results indicate that over 80% of the variation in ground-dwelling insect data can be explained by climatic and edaphic factors, including air and soil temperature, wind speed, soil pH, and humidity. These variables not only shape species composition but also contribute to the ecological separation of different reclamation sites. Clay mine sites in 2017 and 2024 exhibited high diversity and more complex trophic interactions, while limestone sites from earlier years (2012) remained more homogeneous and dominated by fewer taxa. The clustering of years in the PCA plot illustrates the ecological divergence resulting from substrate-specific recovery rates and environmental conditions (Alexander *et al.* 2016; Prastiyo *et al.* 2024).

In conclusion, the patterns observed in ground-dwelling insect communities across reclaimed clay and limestone mine sites indicate that a complex interplay between biological succession and environmental conditions influences reclamation outcomes. High diversity and evenness indices, particularly in clay reclamation sites, suggest that these areas are progressing toward a more balanced and self-sustaining ecosystem. The strong statistical correlations between diversity and factors such as humidity, temperature, and species distribution suggest that successful reclamation must address microclimatic optimisation as much as species reintroduction. Ecosystems with lower dominance and higher evenness are better indicators of ecological stability and resilience, as shown by the reduced dominance values in later reclamation years. These findings underscore the importance of using ground-dwelling insects not only as bioindicators but also as functional agents in ecological recovery. They participate in critical processes, including nutrient cycling, decomposition, and food web stabilisation. Therefore, monitoring soil insect diversity offers a reliable and cost-effective tool for evaluating the success of post-mining land reclamation, with the potential to inform adaptive management practices and

policy decisions aimed at restoring biodiversity and ecosystem function on degraded lands (Talaga *et al.* 2015; Juwarkar *et al.* 2016; Goncalves *et al.* 2021).

## Acknowledgements

Thanks to PT Semen Tonasa for allowing the author to conduct research at the location. Thanks also to the Forest Protection and Insect Laboratory and the Integrated Forestry and Environment Laboratory for facilitating insect identification.

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