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Butterfly community structure in a rehabilitated post-mining tropical rainforest landscape, Sorowako, South Sulawesi, Indonesia

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Abstract. *Nuraeni S, Prastiyo A, Larekeng SH, Ardiansyah A, Aldi, Jufri SW. 2025. Butterfly community structure in a rehabilitated post-mining tropical rainforest landscape, Sorowako, South Sulawesi, Indonesia. Biodiversitas 26: 4761-4774.* Human disturbances, such as mining, can disrupt butterfly communities, which serve as important ecological indicators. This study evaluated butterfly diversity and richness in conservation and non-conservation zones within the mining area of PT Vale, South Sulawesi, Indonesia. Data analysis involved diversity indices, t-tests, and Pearson correlations, with cluster analysis grouping sites and PCA exploring links between butterfly abundance and microclimatic factors. A total of 40 butterfly species belonging to five families, mainly Nymphalidae, Pieridae, and Lycaenidae, were recorded from 18 sampling transects during a four-week field period using standard transect and sweep net methods. The most frequently recorded species was *Catopsilia pomona* (Pieridae) with a relative abundance of 20.00%, followed by *Ideopsis juventa* (Nymphalidae) with 19.80%. Results showed that non-conservation sites had slightly higher diversity (1.43±0.67), richness (5.63±4.94), and evenness (0.48±0.13), while dominance was higher in conservation transects (0.52±0.32). This spatial comparison suggests that human-made habitats may support butterfly diversity but also lead to increased species dominance in more intact environments. The t-test showed a significant difference only in evenness. No significant correlations were found between biodiversity indices and environmental variables based on Pearson's analysis. Cluster analysis identified two main site groups: the first included most conservation transects (SC2, SC5, SC6) and some non-conservation transects (SN2, SN3), while the second contained most non-conservation transects and a few conservation sites (SC4, SC8), indicating overlapping habitat features. PCA revealed that light intensity explained 90.15% of the variation in the first principal component, and altitude explained 79.24% in the second, demonstrating their strong influence on butterfly distribution. These results provide baseline data on butterfly community structure and highlight the ecological differences between conservation and disturbed zones.

Keywords: Community composition, conservation, post-mining rehabilitation, South Sulawesi, tropical insects

INTRODUCTION

Butterflies (Lepidoptera) are among the most recognized bioindicator insect groups (Bonebrake et al. 2010; Parikh et al. 2021), renowned for their extraordinary diversity and high levels of endemism. However, butterfly habitats adjacent to mining activities face significant conservation challenges (Sands 2018). As part of its mining rehabilitation program, PT Vale Indonesia has established the Sawerigading Wallacea Biodiversity Park in Sulawesi, Indonesia, a conservation area aimed at restoring biodiversity, including butterfly populations. Sulawesi is home to 557 butterfly species, 239 of which are endemic (Vane-Wright and de Jong 2003). Butterflies are widely recognized as effective bioindicators of habitat quality due to their sensitivity to microclimatic changes, vegetation structure, and land-use disturbance (Cleary et al. 2005; Choudhary and Chishty 2020).

While butterflies have been extensively studied in natural forests and protected areas, our knowledge of their communities in altered or transitional habitats, particularly those undergoing rehabilitation, is limited. Mining sites, despite their initial in-hospitability, can be transformed into valuable conservation assets through ecological management (Sinnett and Sardo 2020). In Indonesia, studies on butterfly diversity in post-mining restoration contexts, especially in areas with long-term revegetation programs like those of PT Vale, are scarce. Tracking their responses to microhabitat variations, such as light, vegetation structure, and elevation, is crucial for enhancing restoration efforts (Alvarez et al. 2024). While Wiranti et al. (2019) have conducted studies on butterfly presence in some restored habitats, there is still a lack of site-specific baselines within high-endemism regions like Sulawesi. This gap in our knowledge is particularly significant in island ecosystems like Sulawesi, where endemism exacerbates the impact of land-use changes (Koneri and Nangoy 2019). This study aims to fill this gap and provide essential feedback for improving restoration practices.

PT Vale Indonesia, a multinational mining company operating in Sorowako, East Luwu District, South Sulawesi, is a global leader in nickel production and also engages in iron ore mining. Sawerigading Wallacea Park, located within PT Vale's operational area, spans more than 300 hectares. It is part of a comprehensive mining rehabilitation initiative that includes a museum, mining-themed parks, botanical and zoological conservation areas, biodiversity research and development centers, cultural venues, and recreational facilities. A key component of PT Vale's zoological conservation strategy involves rehabilitating mining sites to serve as butterfly habitats. To guide this effort, an initial biodiversity survey is necessary for effective conservation planning (Keeley et al. 2019).

Sulawesi, a key region within Wallacea, is recognized as one of the world's biodiversity hotspots due to its exceptional endemism across multiple taxa (Struebig et al. 2022). The island's unique butterfly fauna reflects its rich ecological and geological history. However, human activities such as mining and deforestation have led to habitat fragmentation, posing a serious threat to butterfly populations (Gebremariam 2024). Habitat restoration through programs like PT Vale's is essential for preserving these species and their environments.

Preliminary observations suggest that current butterfly diversity remains suboptimal in some conservation sectors, indicating a need to evaluate ecological carrying capacity and restoration progress (Curtis et al. 2015). However, with the implementation of habitat engineering, we can enhance this capacity and observe a significant improvement in butterfly diversity. Strategies may include the creation of green corridors that connect high-biodiversity zones to conservation areas (Lynch 2019). Restoring butterfly populations also yields broader ecological benefits. Due to their sensitivity to environmental changes, butterfly diversity is a reliable indicator of habitat rehabilitation success (Firoiu et al. 2024). By fostering butterfly conservation, PT Vale's program contributes to maintaining ecosystem functionality in mining landscapes.

This study addresses that gap by assessing butterfly richness, diversity, and ecological structure across rehabilitated and disturbed habitats within PT Vale's operational area. Sorowako, a transitional tropical rainforest, offers a suitable case study. Butterfly diversity serves as a bioindicator of climate change and human-environment interactions, offering insights into microclimatic sensitivity (Kral-O'Brien et al. 2020). By comparing butterfly diversity in Sawerigading Wallacea Park and nearby non-conservation zones, the study reveals habitat quality and ecological drivers influencing butterfly populations. This work aligns with PT Vale's biodiversity goals, transforming mining sites into ecological reserves that promote Sulawesi's heritage, education, and sustainable tourism. This study hypothesizes that butterfly diversity, richness, evenness, and dominance would be lower in non-conservation areas due to habitat disturbance.

MATERIALS AND METHODS

Study area

This research was conducted at PT Vale Indonesia Tbk, specifically within the Sawerigading Wallacea Park protected zone (02.52692°S, 121.34737°E) and adjacent unprotected area (02.50729°S, 121.33598°E) (Figure 1). Administratively, these locations are situated in Sorowako Sub-district, East Luwu District, South Sulawesi, Indonesia. Sawerigading Wallacea Park includes various habitats such as an arboretum, mining park, biodiversity park, open areas, secondary forest, an artificial lake, and a butterfly garden planted with food sources like pagoda flowers (*Clerodendrum paniculatum*) (Figure 1: location A1-A7). Sawerigading Wallacea Park is a reclaimed area of a former mine (unpeeled land). Meanwhile, the secondary forest of Poci Bukit Butoh is also included in the conservation area which was previously a reclaimed area of a former mine with peeled land (Figure 1: location A8-A9).

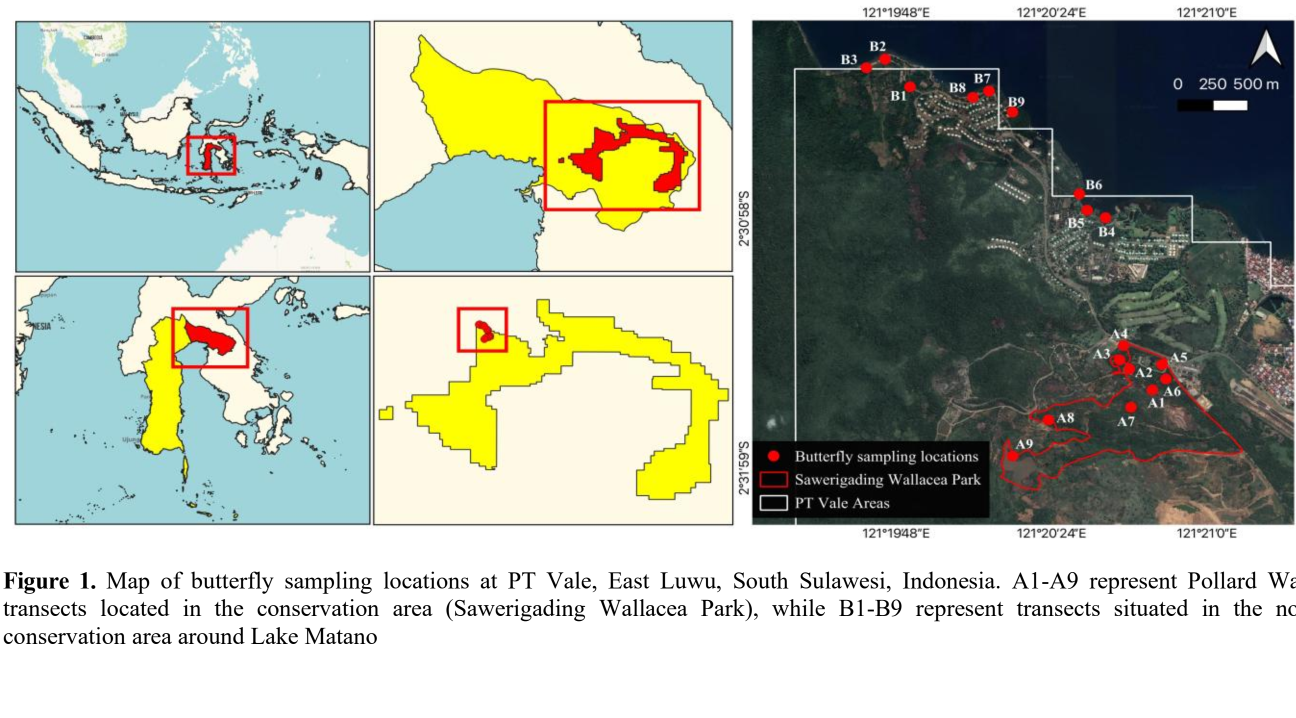

Figure 1. Map of butterfly sampling locations at PT Vale, East Luwu, South Sulawesi, Indonesia. A1-A9 represent Pollard Walk transects located in the conservation area (Sawerigading Wallacea Park), while B1-B9 represent transects situated in the non-conservation area around Lake Matano

In contrast, the non-managed landscape area, the restoration zone, encompasses sections of the coastal waters of Lake Matano, where trees grow along the shoreline, and parts of the area have been developed for tourism. The rehabilitation program, initiated in 2000, involves active reforestation of former secondary forest areas through enrichment planting and site restoration. Tree species used in these efforts include *Casuarina junghuhniana*, *Enterolobium cyclocarpum*, *Acacia mangium*, *Acacia auriculiformis*, *Acacia crassicarpa*, *Senna siamea*, *Macaranga* sp., *Melicope* sp., *Gastonia cutispongia*, *Garcinia mangostana*, *Nephelium lappaceum*, *Mangifera indica*, *Citrus* sp., and *Persea americana*. After 25 years of intervention, these rehabilitated areas, located within conservation zones, have developed into complex mosaics of semi-natural vegetation, intended to support native biodiversity.

Microclimate measurement

Environmental parameters were measured simultaneously with butterfly sampling in the field to ensure a direct correlation between abiotic conditions and species presence. The measured parameters included temperature, humidity, light intensity, wind speed, and altitude. Data collection was conducted at three-time intervals during the day: morning (07:00-09:00), afternoon (11:00-13:00), and noon (15:00-17:00) at the same sites as butterfly sampling to obtain a comprehensive understanding of environmental influences on butterfly distribution. Environmental data from both the managed and impacted habitats are presented in Table 1.

Butterfly data collection

Butterfly surveys were conducted in February 2025 across two contrasting landscapes in East Luwu District, South Sulawesi: the rehabilitated area of Sawerigading Wallacea Park and the anthropogenically disturbed area surrounding Lake Matano. Future monitoring of butterfly species across multiple seasons is encouraged to understand phenological dynamics better, improve species detectability, and guide long-term conservation strategies in post-mining and transitional habitats. The study aimed to assess butterfly diversity across a gradient of ecological disturbance. Sampling employed a stratified purposive design (Forde and Duvvury 2021), with transect placement informed by prior reconnaissance to target areas exhibiting high butterfly activity, such as forest edges, flowering patches, and open-canopy clearings (Basset et al. 2015). This design enhanced species detectability and facilitated robust ecological comparisons across distinct microhabitat types. A total of 18 Pollard Walk transects (9 at each site), each 50 meters long, were established across two primary habitat types (semi-open and shaded canopy). Each transect was georeferenced and sampled using the Pollard Walk method (Pollard and Yates 1993) which observers walk slowly along a fixed path and record all butterflies within a 5-meter belt (2.5 m on each side). The distance between transects was set at a minimum of ≥100 m to ensure data independence and prevent overlapping butterfly communities. Two trained observers moved simultaneously along each transect, maintaining a consistent pace to ensure standardized detection.

Sampling was conducted between 09:00 and 15:00, coinciding with peak butterfly activity under favorable weather conditions (sunny or partly sunny), which improves detectability. Each transect was surveyed once per week over four consecutive weeks, providing temporal coverage to account for fluctuations in species activity. Each survey session lasted 5-6 hours, including time for transect walks, species identification, and data recording. This resulted in 20-24 observer-hours per transect and approximately 180-216 person-hours per site. This standardized and evenly distributed sampling regime ensured consistent observational effort and minimized bias related to time of day, weather, and short-term behavioral variability.

Table 1. The microclimate conditions of the research location

Site	Coordinate	Altitude (m asl)	Temperature (ºC)	Humidity (%)	Light intensity (lux)	Wind speed (m/s)
SC1	121°20'50.532" E, 2°31'36.912" S	430	25.5	80	4,429	0.1
SC2	121°20'42.072" E, 2°31'34.428" S	434	34.0	56	4,180	0.2
SC3	121°20'39.804" E, 2°31'32.196" S	439	31.3	70	3,318	0.2
SC4	121°20'40.704" E, 2°31'28.668" S	434	34.2	55	5,564	0.1
SC5	121°20'49.632" E, 2°31'33.348" S	427	36.1	53	2,516	0.2
SC6	121°20'47.400" E, 2°31'39.576" S	440	31.0	67	2,478	0.2
SC7	121°20'42.432" E, 2°31'43.824" S	517	30.9	62	6,567	0.1
SC8	121°20'23.326" E, 2°31'46.946" S	466	34.2	68	6,794	0.1
SC9	121°20'14.964" E, 2°31'55.848" S	474	33.5	65	1,550	0.3
SN1	121°19'51.240" E, 2°30'25.200" S	407	30.5	63	4,066	0.3
SN2	121°19'45.444" E, 2°30'18.396" S	402	32.2	60	7,360	1.0
SN3	121°19'41.124" E, 2°30'20.520" S	401	33.8	57	9,176	0.8
SN4	121°20'36.528" E, 2°30'57.312" S	403	34.4	52	8,126	1.3
SN5	121°20'32.244" E, 2°30'55.476" S	398	33.1	58	4,899	1.9
SN6	121°20'30.480" E, 2°30'51.516" S	397	34.9	61	5,394	0.8
SN7	121°20'09.528" E, 2°30'26.244" S	405	24.6	82	9,729	0.2
SN8	121°20'05.784" E, 2°30'27.792" S	400	26.6	80	1,951	0.1
SN9	121°20'14.602" E, 2°30'30.835" S	413	28.4	76	2,042	0.2

Note: SC: Conservation site, SN: Non-conservation site

Butterfly identification and documentation

Initial identifications were conducted in the field based on visual morphology, followed by voucher specimen analysis in the lab for final confirmation. During field sampling, all butterfly individuals encountered were recorded. To minimize ecological disturbance, only 1-2 voucher specimens per species were selectively collected per transect for laboratory identification. This selective collection approach is widely accepted in biodiversity studies to maintain population sustainability while enabling accurate taxonomic confirmation (Creer et al. 2016). Captured specimens were preserved and identified at the Forest Protection and Insect Laboratory, Faculty of Forestry, Universitas Hasanuddin, Makassar. Species identification was conducted using species identification keys, including the works of Vane-Wright and de Jong (2003), Widhiono (2015), Koneri et al. (2019), Panjaitan et al. (2020), Ilhamdi et al. (2023), and Kurnianto et al. (2023). Field identification was supported by photographic records taken with a Sony SEL2870 zoom lens and a camera with FE 3.5-5.6/28-70 mm range, which allowed for high-resolution documentation of key morphological features. To enhance taxonomic accuracy and support range validation, all geo-tagged field records were cross-referenced with the iNaturalist citizen science platform, a crucial step that significantly bolstered the study's accuracy. Verified records from iNaturalist were used to validate species identifications, confirm species' presence in South Sulawesi, and facilitate comparison with global biodiversity databases (Molyneaux 2023). Cross-validation with iNaturalist also provided regional occurrence data, aiding in the elimination of false positives and misidentifications in under-documented species. This integration of traditional taxonomy and digital citizen science contributed to more robust and verifiable species-level identifications and improved overall data quality.

Data analysis

Data analysis included calculations of species diversity (H'), richness (R), evenness (E), and dominance (D). An independent t-test was first conducted to compare ecological indices between conservation (SC) and non-conservation (SN) sites. This was followed by a Pearson correlation analysis to assess relationships among biodiversity indices and environmental variables. A hierarchical cluster analysis was then performed using SPSS version 31.0.0.0 to group site locations based on similarity in diversity, richness, evenness, and dominance indices. Lastly, Principal Component Analysis (PCA) was then performed using XLSTAT 2021.2.2 to evaluate the relationship between butterfly abundance and microclimatic conditions in both the conservation and non-conservation zones. PCA was selected because it effectively reduces complex multivariate data into a smaller number of principal components that explain the highest variance in the dataset. This method helps with clear visualization and interpretation of how environmental variables such as temperature, humidity, light intensity, wind speed, and altitude are related to butterfly abundance, without requiring prior assumptions about the data structure. The total number of individuals was calculated using the relative abundance formula to determine the species percentage (Umami et al. 2024):

$$RA = ni/N \times 100\%$$

Relative abundance (RA) is calculated by comparing the number of individuals of a species (ni) to the number of individuals of all species (N). The Shannon-Wiener diversity index was used to estimate the diversity of butterflies in each habitat. This index was calculated using the equation (Krebs 2014):

$$H' = -\Sigma pi \ln pi$$
$$pi = ni/N$$

Where, n is the number of individuals of a species, and N is the total number of individuals. This index measures both species richness and evenness. Higher values of H' indicate greater diversity and more balanced species distributions. The Margalef species richness (R) index was used to estimate butterfly richness in each habitat. This index is calculated using the equation (Ludwig and Reynold 1988):

$$R = S - 1/\ln N$$

Where, S is the number of species found, and N is the total number of individuals. This index highlights species richness and is useful for comparing the number of species across sites regardless of their abundance. The Pielou species evenness index was used to estimate butterfly evenness in each habitat. This index is calculated using the equation (Magurran 1988):

$$E = H'/\ln S$$

Where, H' is the Shannon-Wiener diversity index and S is the number of species. This index measures how evenly individuals are distributed among species; values close to 1 suggest high evenness. The Simpson species dominance index was used to estimate butterfly dominance in each habitat. This index is calculated using the equation (Odum 1993):

$$D = \Sigma (ni/N)^2$$

Where, ni is the number of individuals of each species, and N is the total number of individuals. This index assesses dominance; higher values indicate lower diversity, as a few species dominate the community.

RESULTS AND DISCUSSION

Species distribution and conservation status of butterflies in the mining area, Sorowako, Indonesia

The species accumulation curve (Figure 2) indicates that butterfly richness was consistently higher in non-conservation areas than in conservation areas, with both curves reaching a plateau after the sixth site, suggesting that the sampling effort was sufficient to capture most of the species present. The earlier saturation observed in non-conservation areas implies a more homogeneous and disturbed habitat where adaptable and generalist butterfly species dominate. In contrast, the conservation areas, although hosting fewer species overall, may support more specialized or habitat-sensitive taxa that are harder to detect within the same sampling intensity. This pattern highlights the influence of habitat disturbance on butterfly community composition, with non-conservation areas potentially acting as reservoirs for disturbance-tolerant species. Nonetheless, the plateau in both areas indicates that the survey design effectively represented the local diversity and can serve as a baseline for long-term monitoring. These findings have practical implications for conservation planning, suggesting that a focus on non-conservation areas may be beneficial for preserving butterfly diversity.

A Venn diagram shows the distribution of butterfly species between conservation and non-conservation zones in the PT Vale Indonesia area, South Sulawesi (Figure 3). A total of 24 species were recorded in the conservation zone, with 13 unique species found only in this area, while the non-conservation zone recorded 27 species, including 16 unique species. Ten species were found in both zones, indicating overlapping communities. These findings show that the conservation area in PT Vale continues to support a distinctive and somewhat specific butterfly community. However, the non-conservation area also shows high diversity levels, due to the presence of secondary vegetation or recovering reclamation areas. Differences in species composition between zones reflect the butterfly response to variations in habitat structure, resource availability, and the level of anthropogenic disturbance in the PT Vale post-mining landscape.

The butterfly community structure recorded in the PT Vale Indonesia mining landscape reveals important ecological insights regarding species composition and habitat use across conservation and non-conservation areas. In total, five families and ten subfamilies of butterflies were observed in both habitat types, suggesting that these broad taxonomic groups are resilient and capable of persisting under varying land management conditions (Figure 4). However, more detailed comparisons at the genus and species levels showed differences between conservation and non-conservation areas. The non-conservation area supported a slightly higher species richness, with 27 butterfly species recorded, while the conservation area recorded 24 species. Similarly, 21 genera were found in the non-conservation area, compared to 19 in the conservation zone. Although species richness was somewhat higher in the non-conservation area, the total number of individuals was nearly equal between the two, 204 individuals in the conservation area and 201 in the non-conservation area. This relatively balanced abundance indicates that both areas maintain suitable environmental conditions that support butterfly populations. In total, 40 butterfly species were identified across both areas. The species composition between conservation and non-conservation areas also revealed patterns of uniqueness. Several species, such as *Ideopsis juventa*, *Neptis sappho*, and *Junonia atlites*, were found in both areas, highlighting their ecological flexibility. In contrast, species like *Papilio peranthus* and *Iraota rochana* were restricted to the conservation or non-conservation area, reflecting specific habitat preferences. These findings suggest that while conservation areas play a vital role in preserving butterfly diversity, the surrounding non-conservation landscapes also contribute meaningfully to overall species richness and should not be overlooked in biodiversity management strategies.

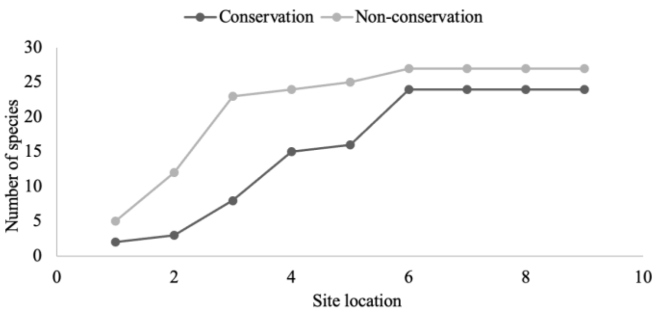

Figure 2. Species accumulation curve across site locations shows that non-conservation areas consistently support more butterfly species than conservation areas, with both curves flattening after site 6

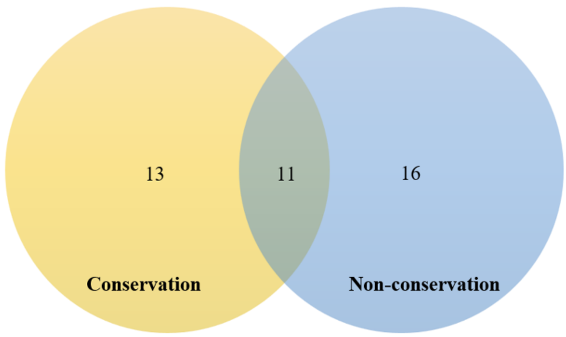

Figure 3. Venn diagram showing butterfly species distribution between conservation and non-conservation zones at PT Vale, Sorowako, South Sulawesi, Indonesia

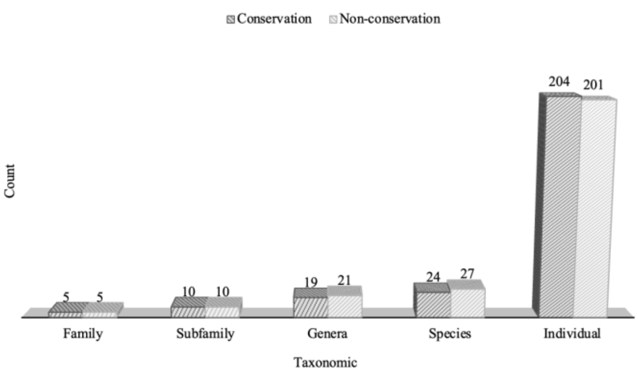

Figure 4. Comparison of butterfly diversity at different taxonomic levels between conservation and non-conservation sites in PT Vale, Sorowako, South Sulawesi, Indonesia

Based on the data in Table 2, butterfly species in the mining area of PT Vale Indonesia show varying levels of relative abundance across conservation and non-conservation zones. The most abundant species overall is *C. pomona* (Pieridae: Coliadinae), with a total relative abundance of 20.00, followed by *I. juventa* (Nymphalidae: Danainae) with 19.8 and *Graphium milon* (Papilionidae: Papilioninae) with 5.19. Notably, *I. juventa* exhibits a high presence in both conservation (14.22) and non-conservation (25.37) zones. Some species, such as *Lexias aeetes*, *Mycalesis perseus*, and *Junonia hedonia*, were more dominant in conservation areas. At the same time, others, like *Euploea algea*, *Junonia almana*, and *G. milon,* were more frequent in non-conservation zones. Several species, including *Catochrysops strabo*, *J. almana*, and *Junonia atlites*, show a relatively balanced distribution across both areas. In contrast, species such as *Discolamps ilissus*, *Parrhasius m-album*, and *Moduza lymire* were found exclusively in non-conservation zones, suggesting a habitat preference or tolerance to disturbed environments.

Table 2. Relative abundance and conservation status of butterfly species in the mining area of PT Vale, South Sulawesi, Indonesia

Family, Subfamily	Species	Abundance			Endemic Wallacea	Permen LHK 2018	IUCN Red List
		A	B	Total			
Lycaenidae							
Polyommatinae	*Anthene emolus* (Godart, 1824)	3.43	0.00	1.73	-	-	NE
Polyommatinae	*Catochrysops panormus* (C. & R. Felder, 1860)	0.00	1.00	0.49	-	-	NE
Polyommatinae	*Catochrysops strabo* (Fabricius, 1793)	6.86	0.00	3.46	-	-	NE
Polyommatinae	*Discolamps ilissus* (C. & R. Felder, 1859)	0.00	1.00	0.49	✓	-	NE
Polyommatinae	*Nacaduba berenice* (Herrich-Schaffer, 1869)	0.00	3.48	1.73	-	-	NE
Polyommatinae	*Zizina otis* (Fabricius, 1787)	2.45	0.00	1.23	-	-	LC
Theclinae	*Arhopala acetes* (Hewitson, 1862)	1.47	0.00	0.74	✓	-	NE
Theclinae	*Iraota rochana* (Horsfield, 1829)	1.96	0.00	0.99	-	-	NE
Theclinae	*Parrhasius m-album* (Boisduval & Le Conte, 1833)	0.00	1.00	0.49	-	-	NE
Theclinae	*Strymon melinus* (Hubner, 1818)	0.00	1.00	0.49	-	-	NE
Nymphalidae							
Danainae	*Euploea algea* (Godart, 1819)	0.00	6.47	3.21	-	-	NE
Danainae	*Ideopsis juventa* (Cramer, 1777)	14.22	25.37	19.8	-	-	NE
Danainae	*Parantica cleona* (Fruhstorfer, 1892)	0.00	3.98	1.98	✓	-	NE
Limenitidinae	*Moduza lymire* (Hewitson, 1859)	0.00	1.00	0.49	✓	-	NE
Limenitidinae	*Euthalia amanda* (Hewitson, 1862)	0.49	0.00	0.25	✓	-	NE
Limenitidinae	*Lexias aeetes* (Hewitson, 1861)	5.88	0.00	2.96	✓	-	NE
Limenitidinae	*Neptis sappho* (Pallas, 1771)	0.49	1.49	0.99	-	-	NE
Nymphalinae	*Hypolimnas bolina (*Linnaeus, 1758)	0.00	1.49	0.74	-	-	NE
Nymphalinae	*Junonia almana* (Linnaeus, 1758)	0.00	6.97	3.46	-	-	LC
Nymphalinae	*Junonia atlites* (Linnaeus, 1763)	3.43	3.48	3.46	-	-	NE
Nymphalinae	*Junonia erigone* (Cramer, 1779)	0.00	2.49	1.23	-	-	NE
Nymphalinae	*Junonia hedonia* (Linnaeus, 1764)	3.92	4.48	4.2	-	-	NE
Nymphalinae	*Rhinopalpa polynice* (Cramer, 1779)	0.00	1.00	0.49	-	-	NE
Satyrinae	*Faunis menado* (Rober, 1896)	1.47	0.00	0.74	✓	-	NE
Satyrinae	*Melanitis leda* (Linnaeus, 1758)	1.96	0.00	0.99	-	-	LC
Satyrinae	*Mycalesis perseus* (Fabricius, 1775)	3.92	0.00	1.98	-	-	NE
Satyrinae	*Ypthima baldus* (Fabricius, 1775)	5.88	0.00	2.96	-	-	NE
Satyrinae	*Ypthima pandocus* (Moore, 1857)	1.47	1.49	1.48	-	-	NE
Papilionidae							
Papilioninae	*Graphium androcles* (Boisduval, 1836)	0..00	1.00	0.49	✓	-	NE
Papilioninae	*Graphium milon* (C. & R. Felder, 1864)	1.47	8.96	5.19	✓	-	NE
Papilioninae	*Papilio demoleus* (Linnaeus, 1758)	2.45	0.00	1.23	-	-	NE
Papilioninae	*Papilio gigon* (C. & R. Felder, 1864)	1.96	1.00	1.48	✓	-	NE
Papilioninae	*Papilio peranthus* (Fabricius, 1787)	0.00	0.50	0.25	-	-	NE
Papilioninae	*Troides helena* (Linnaeus, 1758)	0.49	0.00	0.25	-	Protected	LC
Papilioninae	*Troides hypolitus* (Cramer, 1775)	0.00	1.00	0.49	✓	Protected	LC
Pieridae							
Coliadinae	*Catopsilia pomona* (Fabricius, 1775)	25.98	13.93	20.00	-	-	NE
Coliadinae	*Catopsilia scylla* (Linnaeus, 1763)	1.47	1.99	1.73	-	-	NE
Coliadinae	*Eurema tominia* (Vollenhoven, 1865)	0.00	1.00	0.49	-	-	LC
Pierinae	*Leptosia nina* (Fabricius, 1793)	0.49	0.50	0.49	-	-	NE
Riodinidae							
Nemeobiinae	*Abisara echerius* (Stoll, 1790)	6.37	2.99	4.69	-	-	NE

Notes: A: Conservation area; B: Non-conservation area. The check mark (✓) indicates that the species meets the corresponding criterion listed in the column (e.g., Wallacea endemic, protected under Permen LHK 2018). The (-) indicates that there is no data or the criterion does not apply to the species

A total of 11 butterfly species is identified as endemic to the Wallacea (Sulawesi) biogeographic region, namely *D. ilissus*, *A. acetes*, *P. cleona*, *M. lymire*, *E. amanda*, *L. aeetes*, *F. menado*, *G. androcles*, *G. milon*, *P. gigon*, and *T. hypolitus*, showing the unique biodiversity of the region (Ahmad and Hamzah 2016). These endemic species are distributed across different families and subfamilies, with Nymphalidae being particularly prominent. Their presence in both conservation and non-conservation zones emphasizes the significance of habitat heterogeneity in maintaining native species diversity, even though most are not yet listed under national protection regulations or globally assessed. Only two butterfly species, *T. helena* and *T. hypolitus*, are officially recognized as protected under the Indonesian Ministry of Environment and Forestry Regulation (Permen LHK 2018). These species are also categorized as Least Concern (LC) in the IUCN Red List, suggesting their populations are stable on a global scale. However, they are still considered important at the national level. Other species, such as *J. almana*, *M. leda*, and *E. tominia*, also fall into the LC category without being nationally protected. Meanwhile, a majority of the species recorded are still categorized as Not Evaluated (NE), including some that are abundant or endemic. This reveals a gap in global conservation assessments for tropical butterflies and underscores the need for local monitoring and documentation to inform conservation priorities. Butterflies from the subfamilies Danainae, Nymphalinae, and Papilioninae appear in both conservation categories and show varied statuses. For example, *I. juventa*, *J. hedonia*, and *P. rigon* are neither endemic nor protected, yet they are common in the area. Similarly, *C. pomona*, which shows high abundance, remains unevaluated by the IUCN and unlisted nationally. These patterns reflect a community composed of a mixture of generalist and specialist species, some of which are ecologically significant despite lacking formal conservation status. The table as a whole suggests that both conservation and non-conservation zones contribute to sustaining butterfly populations with diverse conservation needs and ecological characteristics.

Diversity of butterflies in the mining area, Sorowako, South Sulawesi, Indonesia

The index analysis in the mining area of PT Vale Indonesia reveals minimal differences in butterfly community structure between conservation and non-conservation zones (Figure 5). The diversity index was higher in non-conservation sites (1.43±0.67) than in conservation sites (0.97±0.80), suggesting that butterfly communities are more varied in areas exposed to human activity. Species richness followed a similar pattern, with a value of 5.63±4.94 in non-conservation zones compared to 4.06±3.78 in conservation zones, indicating a greater number of species in disturbed habitats, possibly due to microhabitat heterogeneity or transitional vegetation types. Evenness was also notably higher in non-conservation areas (0.48±0.13) than in conservation areas (0.29±0.21), showing that species were more evenly distributed in the former. At the same time, a few dominant species may more influence conservation zones. In contrast, the dominance index was higher in conservation zones (0.52±0.32) than in non-conservation zones (0.32±0.19), reflecting a greater concentration of individuals in fewer species within protected habitats. These results suggest that non-conservation areas support more resilient or opportunistic butterfly species, whereas conservation zones host less evenly distributed but potentially more specialized communities. These patterns were further examined using an independent t-test to determine whether the observed differences in community indices between conservation and non-conservation areas were statistically significant.

The results are presented in Table 3, highlighting that only the evenness index exhibited a significant difference between the two landscape types ($p<0.05$), while other indices, such as diversity, richness, and dominance, did not differ significantly. Although diversity, richness, and dominance indices were higher in the non-conservation area, the differences were not statistically significant. This outcome reflects the relatively homogeneous microhabitat structure across both zones, which limits ecological contrast and community turnover. Such uniformity can constrain species sorting mechanisms and reduce detectable variation in butterfly assemblages. Furthermore, as the survey was conducted only in February, the results do not capture seasonal shifts in species composition and abundance that commonly occur in tropical ecosystems. Longitudinal monitoring across multiple seasons is necessary to understand better phenological dynamics and the full extent of community variation in post-mining and rehabilitated landscapes (Ruslan et al. 2023).

Table 3. Results of an independent t-test for butterfly community indices

Index	Conservation	Non-conservation
	Mean±SD	Mean±SD
Diversity (H')	0.97±0.80	1.43±0.67
Richness (R)	4.06±3.78	5.63±4.94
Evenness (E)*	0.29±0.21	0.48±0.13
Dominance (D)	0.52±0.32	0.32±0.19

Note: Values are presented as Mean±Standard Deviation (SD). Asterisk (*) indicates a statistically significant difference at $p<0.05$

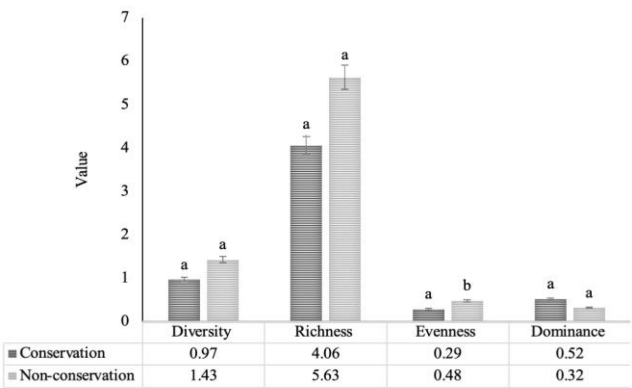

Figure 5. Index values for diversity, richness, evenness, and dominance of butterflies in the mining area PT Vale Indonesia, South Sulawesi, Indonesia

Relationship between microclimate and butterfly abundance

Correlation analysis (Table 4) revealed significant relationships between the diversity index and several environmental parameters as well as other community indices. The diversity index showed a very strong and positive correlation with species richness (r: 0.93, p<0.01), evenness (r: 0.94, p<0.01), and species abundance (r: 0.86, p<0.01), as well as with species count (r: 0.92, p<0.01). Conversely, the diversity index had a very strong negative correlation with the dominance index (r: -0.94, p<0.01), indicating that higher dominance of a single species tends to reduce overall community diversity. Additionally, temperature showed a highly significant negative correlation with humidity (r: -0.90, p<0.01). At the same time, other variables such as light intensity, wind speed, and elevation had no significant correlation with the diversity index but exhibited patterns that may be ecologically meaningful.

Figure 6 presents a hierarchical cluster analysis of butterfly community composition across both conservation (SC) and non-conservation (SN) sites. The clustering pattern reveals two main groups. The first cluster primarily includes SC sites (SC2, SC5, SC6, SC3) along with a few SN sites (SN2, SN3), indicating a high degree of similarity in community structure. The second cluster comprises most SN sites (SN1, SN4, SN5, SN6, SN7, SN8, SN9) as well as some SC sites (SC4, SC8, SC9), indicating an overlapping species composition driven by similar environmental conditions or transitional habitats. The cluster distance also shows that SC2 and SC5 are the most similar in terms of species composition, while SC4 stands out as the most distinct from all other locations. This pattern is supported by the R values, which are very close for SC2 (0.44) and SC5 (0.38), but considerably different from SC4, which shows a much higher R value of 6.73. This indicates that both habitat type and environmental conditions shape species similarity. However, the absence of ecological trait data limits deeper interpretation of functional differences across sites. Future research should incorporate trait-based analyses to enhance ecological understanding.

PCA was conducted to reduce dimensionality and to identify the main environmental and ecological variables contributing to butterfly diversity and richness in the mining landscape of Sorowako, South Sulawesi. The results revealed that the first Principal Component (PC1) accounted for nearly all the variation in the dataset (99.96%), while the second component (PC2) contributed only marginally (0.04%). This indicates that most of the observed variability in butterfly communities across sites was primarily driven by the dominant variables represented in PC1. Further details on the eigenvalues and the percentage of explained variance are provided in Table 5.

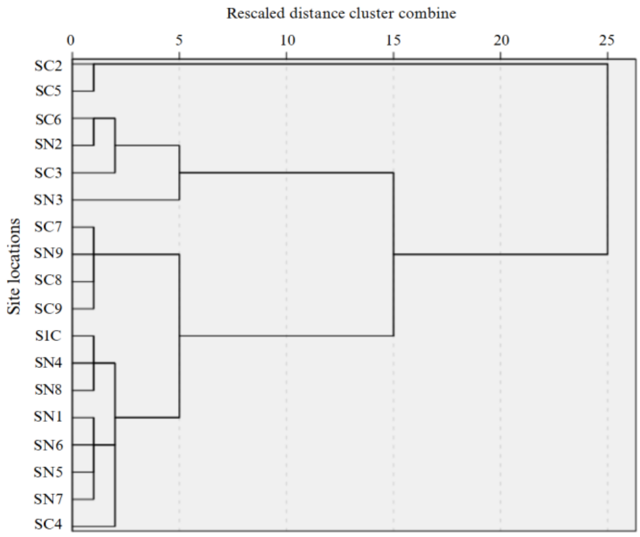

Figure 6. Hierarchical cluster analysis (dendrogram) of butterfly community composition across all site locations in the Sorowako mining area, South Sulawesi, Indonesia. SC: Conservation site; SN: Non-conservation site. Clustering is based on similarity in diversity index, richness index, evenness index, and dominance index

Table 4. Pearson correlation matrix between butterfly diversity indices and environmental variables in the mining area, Sorowako, South Sulawesi, Indonesia

	H'	R	E	D	N	S	T	M	I	W	A
H'	1										
R	0.93**	1									
E	0.94**	0.78**	1								
D	-0.94**	-0.75**	-0.97**	1							
N	0.86**	0.91**	0.67**	-0.73**	1						
S	0.92**	1.00**	0.78**	-0.75**	90.00**	1					
T	-0.58	0.11	-0.23	0.20	0.15	0.11	1				
M	0.01	-0.15	0.18	-0.17	-0.17	-0.16	-0.90**	1			
I	0.33	0.31	0.33	-0.37	0.25	0.31	0.03	-0.18	1		
W	0.28	0.21	0.34	-0.29	0.12	0.22	0.35	-0.46	0.34	1	
A	-0.36	-0.25	-0.43	0.34	-0.14	-0.26	0.11	-0.02	-0.16	-0.50*	1

Note: **: Correlation is significant at the 0.01 level, *: Correlation is significant at the 0.05 level. H': Diversity index, R: Richness index, E: Evenness index, D: Dominance index, N: Abundance, S: Number of species, T: Temperature, M: Humidity, I: Light intensity, W: Wind speed, A: Altitude

Based on the PCA (Table 6), light intensity showed the highest contribution to PC1, accounting for 90.15% of the variation, indicating its dominant role in shaping the main component. Other variables such as the diversity index, richness index, evenness index, and dominance index contributed minimally to PC1, each explaining just over 1% of the variance. Wind speed also contributed modestly to PC1 with 1.24%, while altitude had an almost negligible role at just 0.03%. In contrast, altitude became the most influential variable in PC2, contributing 79.24%, followed by abundance at 5.41%. Variables such as evenness index and dominance index also had relatively higher contributions to PC2 compared to PC1, each exceeding 2%, suggesting their importance in explaining secondary patterns in the dataset. This separation in variable influence indicates that PC1 is primarily driven by light intensity, while PC2 is governed by altitude and abundance.

The PCA biplot (Figure 7) visually separates conservation and non-conservation areas based on environmental and ecological variables. Light intensity (I) is positioned far to the right along the PC1 axis, indicating a strong association with the non-conservation area, which aligns with its dominant contribution to PC1. In contrast, all other variables cluster closely on the left side of the plot, suggesting they are more characteristic of the conservation area. Altitude (A), which plays a major role in PC2, appears slightly elevated along that axis, reinforcing its relevance in distinguishing conservation-related patterns. This biplot supports the interpretation that environmental factors like light intensity and altitude significantly differentiate butterfly habitats between conservation and non-conservation zones.

Discussion

The high species richness and low dominance of butterflies in the post-mining landscape of Sorowako indicate that ecological recovery is underway. This pattern aligns with ecological principles stating that areas with a high diversity of microhabitats and resource heterogeneity support greater species coexistence (Schalkwyk et al. 2021). These findings are consistent with restoration theory, which emphasizes the importance of plant diversity and habitat heterogeneity in sustaining diverse ecological communities (Goded et al. 2019; Korkiatupa et al. 2023). A similar trend was reported in the Brazilian Amazon, where butterfly richness and low dominance were observed in naturally regenerating areas (Neves et al. 2021). In Borneo, Foster et al. (2011) found that restoration efforts using native plant species and maintaining connectivity with primary forests were crucial in supporting healthier butterfly communities. Likewise, studies in eastern Brazil showed that natural regeneration was more effective in supporting butterfly diversity than monoculture plantations (Barlow et al. 2007). These comparisons affirm that restoration success is driven by both vegetation structure and ecological connectivity, regardless of regional context. These findings confirm that butterfly diversity can serve as a reliable indicator of successful habitat restoration, as also demonstrated in other tropical landscapes (Solis-Gabriel et al. 2017; Swarnali et al. 2019). The recorded butterfly species are illustrated in Figure 8, supporting visual confirmation of species richness and taxonomic composition.

Table 5. Eigenvalues and explained variance from PCA

Principal Component (PC)	Eigenvalue	% Variance	Cumulative %
PC1	2.00	99.96	99.96
PC2	0.00	0.04	100.00

Table 6. PCA results of variable contributions

Parameters	PC1 (%)	PC2 (%)
Diversity index	1.23	2.32
Richness index	1.22	2.28
Evenness index	1.24	2.41
Dominance index	1.25	2.45
Abundance	0.45	5.41
Number of species	1.13	1.59
Temperature	1.10	0.83
Humidity	0.95	0.21
Light intensity	90.15*	0.75
Wind speed	1.24	2.53
Altitude	0.03	79.24*

Note: Asterisk (*) values indicate the highest contributing variable for each principal component axis (PC1 and PC2)

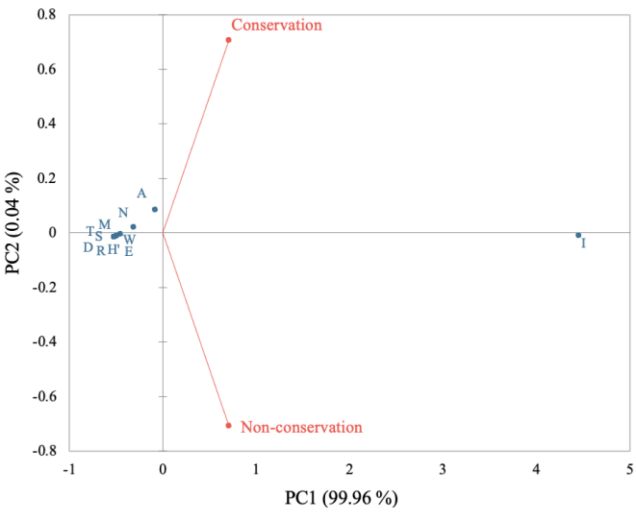

Figure 7. PCA biplot showing the clustering of environmental and biological variables related to butterfly (Lepidoptera) diversity and richness in the post-mining landscape of Sorowako, South Sulawesi, Indonesia. Arrows indicate site groupings based on conservation status. The PCA axes represent variance explained by PC1 (99.96%) and PC2 (0.04%). Variable codes: H': Diversity index, R: Richness index, E: Evenness index, D: Dominance index, N: Abundance, S: Number of species, T: Temperature, M: Humidity, I: Light intensity, W: Wind speed, A: Altitude

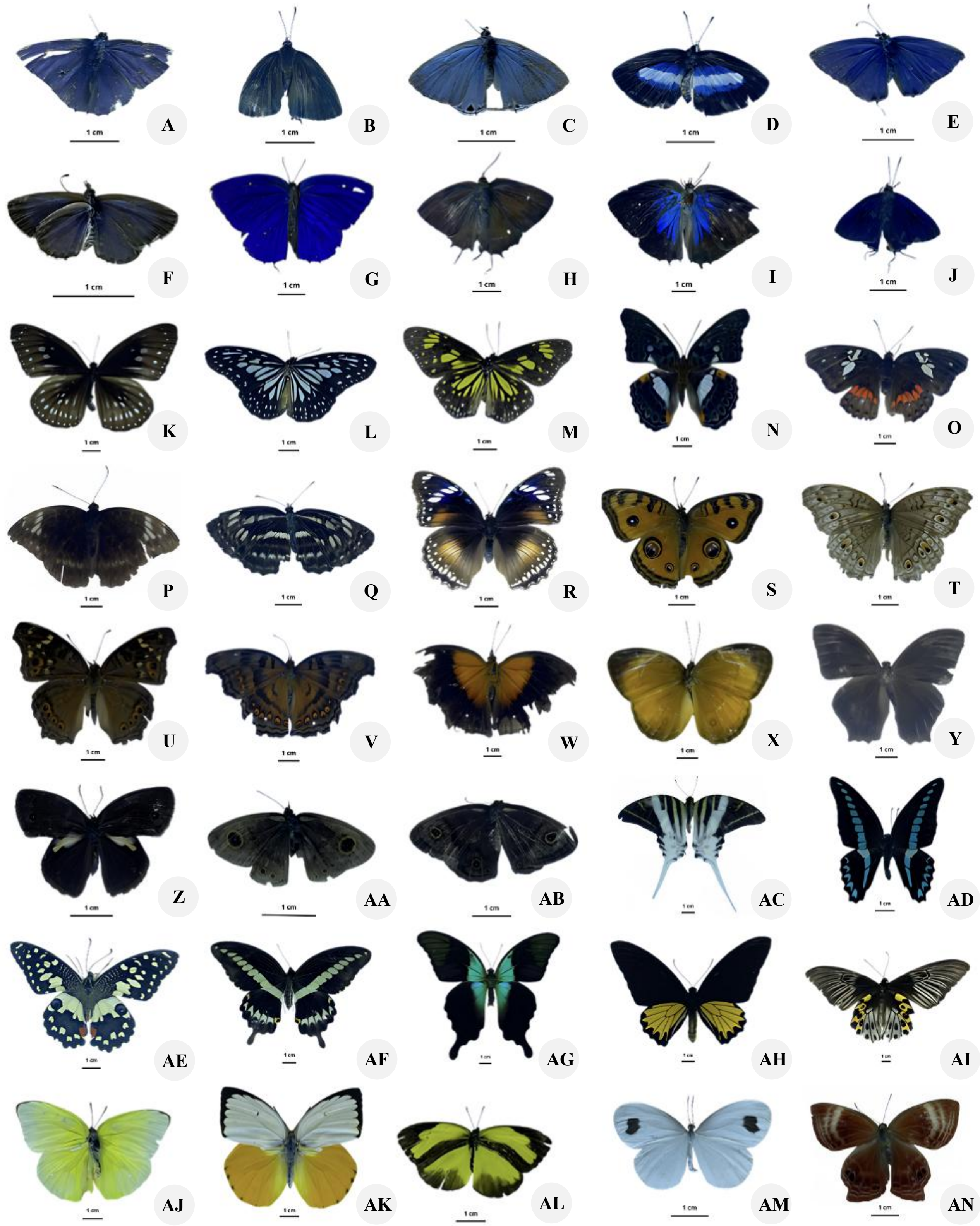

Figure 8. Butterflies recorded in the post-mining landscape by PT Vale, South Sulawesi, Indonesia. A: *Anthene emolus*, B: *Catochrysops panormus*, C: *Catochrysops strabo*, D: *Discolamps ilissus*, E: *Nacaduba berenice*, F: *Zizina otis*, G: *Arhopala acetes*, H: *Iraota rochana*, I: *Parrhasius m-album*, J: *Strymon melinus*, K: *Euploea algea*, L: *Ideopsis juventa*, M: *Parantica cleona*, N: *Moduza lymire*, O: *Euthalia amanda*, P: *Lexias aeetes*, Q: *Neptis sappho*, R: *Hypolimnas bolina*, S: *Junonia almana*, T: *Junonia atlites*, U: *Junonia erigone*, V: *Junonia hedonia*, W: *Rhinopalpa polynice*, X: *Faunis menado*, Y: *Melanitis leda*, Z: *Mycalesis perseus*, AA: *Ypthima baldus*, AB: *Ypthima pandocus*, AC: *Graphium androcles*, AD: *Graphium milon*, AE: *Papilio demoleus*, AF: *Papilio gigon*, AG: *Papilio peranthus*, AH: *Troides helena*, AI: *Troides hypolitus*, AJ: *Catopsilia pomona*, AK: *Catopsilia scylla*, AL: *Eurema tominia*, AM: *Leptosia nina*, AN: *Abisara echerius*. Scale bar 1 cm

Endemic butterfly species from Wallacea, such as *D. ilissus*, *A. acetes*, *P. cleona*, *M. lymire*, *E. amanda*, *L. aeetes*, *F. menado*, *G. androcles*, *G. milon*, *P. gigon*, and *T. hypolitus*, show a strong dependence on stable and undisturbed natural habitats. This ecological dependence makes them highly vulnerable to ecosystem changes caused by deforestation and land-use conversion. According to Futuyma and Moreno (1988), highly specialized species, especially those dependent on specific host plants or unique habitats, tend to have low ecological flexibility and are more susceptible to habitat alterations. Such legal protection helps address the gap in global conservation systems like the IUCN Red List, which has yet to evaluate the majority of tropical insect species (Barahona-Segovia and Zúñiga-Reinoso 2021; Miličić et al. 2021; Ong et al. 2025). In contrast, non-endemic species with broader ranges are still able to persist in regenerating areas, indicating that life history traits and endemic status significantly influence species' responses to habitat disturbance (Maulany et al. 2024; Singh et al. 2024). These contrasting responses reflect a central concept in conservation ecology: species with narrow ranges and low habitat tolerance are more susceptible to fragmentation and environmental change (Suryanto 2020; Budiaman et al. 2025).

This reflects a significant gap in data concerning the distribution and conservation status of tropical insects. Such a situation aligns with the concept of the Wallacean shortfall, which highlights the lack of biogeographic information for species in tropical regions like Wallacea (Vergara-Asenjo et al. 2023). The absence of reliable data complicates the development of risk-based conservation strategies, particularly in biodiversity-rich areas (Collen et al. 2008; Montejo-Kovacevich et al. 2022). For instance, *P. gigon* is known to have commercial value in the collector market and faces pressure from habitat loss, yet it is not currently listed as threatened on the IUCN Red List; field observations, however, suggest that its population is declining. This situation illustrates the risk of silent extinctions, as described by Warren et al. (2021), in which species decline goes undetected at the global level.

In tropical regions, habitat pressures tend to be high, while scientific documentation remains limited. Locally driven conservation efforts based on field observations can help fill this global information gap (Wang et al. 2020). Butterflies serve as reliable ecological indicators, as changes in their populations reflect shifts in environmental conditions (López-Vázquez et al. 2024). Long-term monitoring systems, vulnerability assessments based on local data, and spatial mapping from direct observations are essential for strengthening regional conservation policies (Suryanto 2020; Gebremariam 2024; Singh et al. 2024).

Ecological restoration on mining sites should imitate natural succession and involve locally adapted plant species that support a diverse insect population. Replanting native species adapted to local soil and climate can restore habitats for various animals, including butterflies. Ojija (2024) and Sánchez and Lara (2024) highlight that native plants are crucial for providing insect habitats. Poorter et al. (2024) suggested that pioneer species help develop more diverse communities through successional pathways. Structurally layered vegetation, such as shrubs and various plant forms, creates microhabitats that butterflies utilize for foraging, reproduction, and shelter. Research by Neal et al. (2024) demonstrated that complex vegetation structures enhance butterfly richness. Furthermore, connected habitats facilitate butterfly dispersal and recolonization of disturbed areas. This finding aligns with Ancillotto et al. (2024) and Gordon et al. (2024), who showed that habitat connectivity influences butterfly movement. Habel et al. (2024) also noted that natural disturbances shape the structure of tropical ecosystems. These findings collectively point to the spatial habitat configuration and quality in driving successful recolonization.

Environmental stressors such as soil contamination and heavy metal pollution reduce the potential for butterfly population recovery in mining areas. Contaminated soils affect the nutritional quality of host plants, negatively impacting larval development and reproductive success (Heliovaara et al. 2018; Han et al. 2022). Heavy metals and toxic residues interfere with insect physiology, leading to behavioral changes and reduced fertility (Oliveira et al. 2022). In addition, altered soil chemistry from mining reduces plant diversity, further degrading butterfly habitats (Wang et al. 2022). Ecological restoration in mining landscapes, therefore, requires comprehensive soil and water remediation, not just vegetation replanting, to create suitable conditions for pollinators like butterflies (Prakash and Budhwan 2024). Butterfly communities in Gunung Meja, West Papua, were found to be highly diverse across habitat types, with species richness and abundance significantly influenced by environmental parameters and human disturbances near settlements (Panjaitan et al. 2016).

The study findings from Sorowako indicate that butterfly conservation in post-mining landscapes depends on habitat quality, physical environmental conditions, and species-specific adaptive capacities. Environmental gradients such as elevation, light intensity, and humidity shape distinct ecological zones that influence butterfly community structure (Montejo-Kovacevich et al. 2020). Tropical butterflies are highly sensitive to changes in microclimate, particularly temperature and canopy cover (Wang 2023). Long-term conservation requires landscape-wide strategies that include habitat restoration, improving ecological connectivity, data-driven management, and community involvement. Ecological corridors, native vegetation enhancement, and climate-adaptive management help ensure the stability of butterfly populations (Krumins and Klavins 2025). Other studies also show that successful butterfly conservation in tropical regions depends heavily on habitat structure and vegetative connectivity (Whitworth et al. 2016; Qianwen et al. 2022).

Comparative studies reinforce the patterns observed in Sorowako. In the Brazilian Amazon, butterfly diversity was significantly higher in areas with complex secondary vegetation than in unrestored open-pit mines (Neves et al. 2021). In Kalimantan, Indonesia, population recovery was stronger in areas restored with native plant species and high connectivity to primary forests (Nugroho et al. 2022).

Similar patterns were found in the Atlantic Forest of eastern Brazil, where natural regeneration supported specialist butterfly species more effectively than monoculture plantations (Barlow et al. 2007). In California, butterfly distribution was closely linked to water availability, canopy cover, and floral diversity (Schneider et al. 2020). In Ghanaian bauxite mines, the presence of host plants, ground cover, and connectivity to native forests was associated with increased butterfly and insect richness (Kyerematen et al. 2014). Butterfly diversity in degraded areas of Central Kalimantan is shaped by habitat degradation, not fragmentation, with specific species indicating ecological conditions across habitat types (Harmonis and Saud 2017). Butterflies in Endau-Rompin Johor National Park, Malaysia, remain highly diverse and show strong potential as a nature-based tourism attraction despite habitat degradation (Ismail et al. 2020). These findings collectively underscore that successful restoration in tropical mining landscapes relies on complex vegetation structure, habitat connectivity, and the presence of larval host and nectar plants. By synthesizing recent studies across Southeast Asia and Wallacea, this analysis strengthens the ecological interpretation of butterfly response to post-mining restoration.

This study revealed that butterflies are effective indicators of ecological conditions in post-mining landscapes due to their sensitivity to changes in light, elevation, and vegetation complexity. Lowland areas with higher light availability and diverse local flora support greater species richness and abundance, particularly when food sources are available year-round. However, this study was limited by temporal constraints, as field sampling was conducted only in February, which did not fully capture seasonal variations in butterfly communities. Field observations indicate population declines in some of these species due to habitat degradation. These findings highlight the need for urgent habitat protection and vegetation restoration tailored to the specific larval and adult feeding requirements of each species. The ecological significance of these findings underscores the value of butterflies as bioindicators for monitoring ecosystem health and evaluating the success of restoration in post-mining tropical landscapes. Community involvement through citizen science monitoring and integration of field data into national biodiversity databases is not just a suggestion, but a crucial part of the solution. It can serve as interim conservation measures pending formal assessments, and its importance cannot be overstated. Thus, butterfly conservation strategies in tropical mining regions must be designed adaptively and participatively, combining scientific data and habitat restoration to support long-term species persistence and ecosystem function. This study provides a scientific foundation for policy recommendations on mine rehabilitation, biodiversity offsets, and conservation planning in Sulawesi's mining zones.

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