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Collembola diversity across three successional stages in a reclaimed tropical mining tailing site, Central Papua, Indonesia

SRIHARTATI HARTO[1], MUSYAFA[2,♥], SUMARDI[2], SURYO HARDIWINOTO[2], RISANDIKA ASTANOVIA DEWI[1], PRAKTITA PURADYATMIKA[3], ROBERTH SARWOM[3]
[1]Graduate Program of Forestry Science, Faculty of Forestry, Universitas Gadjah Mada. Jl. Agro No 1, Bulaksumur, Sleman 55281, Yogyakarta, Indonesia
[2]Departement of Silviculture, Faculty of Forestry, Universitas Gadjah Mada. Jl. Agro No 1, Bulaksumur, Sleman 55281, Yogyakarta, Indonesia.
Tel./fax.: +62-274-512102, ♥email: musyafa@ugm.ac.id
[3]Division of Environmental, PT. Freeport Indonesia. Jl. Mandala Raya Selatan No.2, Kuala Kencana, Timika 99920, Papua, Indonesia

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Abstract. *Harto S, Musyafa, Sumardi, Hardiwinoto S, Dewi RA, Puradyatmika P, Sarwom R. 2025. Collembola diversity across three successional stages in a reclaimed tropical mining tailing site, Central Papua, Indonesia. Biodiversitas 26: 2210-2220.* Reclamation of tailing-impacted land by PT Freeport Indonesia aims to mitigate soil degradation and restore the underground microfauna ecosystem. Collembolas are utilized as bioindicators to evaluate reclamation success. This study investigated Collembola diversity across three reclamation stages (10, 14, and 21 years) and natural forest, along with their relationships to soil fertility and heavy metal contamination. Sampling was conducted across three soil types and three litter types, totaling 840 sample plots, using a modified Berlese funnel extraction. According to the Shannon-Wiener Diversity Index, Collembola diversity was classified as high in natural forests and 21-year-old reclaimed areas and moderate in 14- and 10-year-old areas. Canonical Correspondence Analysis (CCA) showed that organic matter, carbon, and phosphorus were key factors influencing Collembola's presence. Metal analysis indicated associations between Entomobryidae and Poduridae with lead (Pb) in the oldest reclaimed site, while Neanuridae correlated with mercury (Hg) in the 14-year site. Collembola's diversity and species richness increased with the reclamation age, highlighting the importance of reclamation duration in supporting ecosystem recovery. These findings emphasize the value of long-term reclamation in enhancing soil microfauna communities, improving soil fertility, and guiding sustainable land management in post-mining landscapes.

Keywords: Bioindicator, Collembola diversity, metal contaminants, reclamation period, tailing

INTRODUCTION

Tailings are fine-grained residues generated during the extraction of valuable minerals from ore. At PT Freeport Indonesia, tailings are transported through a riverine system to a lowland deposition site known as the Modified Ajkwa Deposition Area (ModADA), covering approximately 230 square kilometers (Puradyatmika 2020). This deposition process causes significant physical and chemical changes in the soil, often leading to degradation, reduced fertility, and disturbances in plant growth and soil organism activity. According to Ma et al. (2023), such anthropogenic alterations can impair ecological processes and reduce the functional integrity of subsurface ecosystems. In response, reclamation programs aim to restore soil conditions and recover lost ecosystem services.

Within the broader framework of soil restoration, arthropods, particularly Collembola, play a crucial ecological role. These microarthropods contribute to the decomposition of organic matter and facilitate nutrient cycling (Potapov et al. 2020). Their detritivores behavior enhances litter breakdown and improves soil structure (Gao et al. 2018). Owing to their ecological sensitivity and functional importance, Collembola are increasingly recognized as bioindicators for evaluating the success of reclamation and revegetation initiatives (dos Santos et al. 2018).

In Indonesia, the potential of Collembola as a soil health indicator in post-mining landscapes has been well documented. For example, Nurtjahya et al. (2007) observed a positive correlation between the duration of *Acacia mangium* revegetation and the density of Collembola populations in reclaimed tin mines on Bangka Island. Chairunnisa et al. (2022) reported that Collembola diversity is closely tied to soil fertility levels in former mining areas. Similarly, Dewi et al. (2024) demonstrated the relevance of Collembolas as indicators of revegetation success, with community composition varying based on the length of rehabilitation.

Globally, the ecological importance of Collembola has led to the development of monitoring tools such as the QBS-ar index (Soil Biological Quality-Arthropods), widely used in Europe to assess soil biological conditions (Menta et al. 2018). Collembola's acute sensitivity to environmental disturbances, combined with their specialized habitat preferences, makes them effective in detecting changes in soil compaction, microhabitat structure, and organic matter content (George et al. 2017). As representatives of soil mesofauna, variations in their communities are valuable indicators of shifts in overall soil ecosystem health and nutrient cycling processes (Lagendijk et al. 2022).

At PT Freeport Indonesia, environmental monitoring has included assessments of soil fauna since 2006, particularly in areas impacted by tailings deposition and reclamation. Initial studies on mesofauna were undertaken through undergraduate research at Universitas Cenderawasih by Wamafma et al. (2009) and the Universitas Papua by Djuana et al. (2012). Further collaborative research with Indonesian academic institutions focused on various aspects of ecological recovery, including vegetation dynamics, soil formation, animal diversity, and aquatic resources. A 2010 study by the Universitas Papua provided a comprehensive evaluation of microorganisms and mesofauna in tailings zones.

Despite these efforts, no comprehensive research has specifically targeted Collembola communities over the 21-year reclamation period from 2001 to 2022. This represents a notable knowledge gap, given the proven value of Collembolas as bioindicators. Data from the West Embankment could offer baseline insights for long-term ecological monitoring and help identify species associated with different reclamation stages. Moreover, understanding Collembola diversity in relation to reclamation age and tailings history, such as the 50-year-old deposits in the Old West Embankment, can inform future soil management and land-use planning, including experimental agricultural development in sites like MP-21.

Accordingly, this study aims to evaluate and compare Collembola diversity across three stages of land reclamation. It is hypothesized that older, more stabilized areas (reclaimed from 2001 to 2022) support higher diversity than newer sites (reclaimed from 2012 to 2022), indicating gradual improvement in soil ecosystem conditions.

MATERIALS AND METHODS

Study area

This research was conducted in the reclamation area of PT. Freeport Indonesia, located in Mimika District, Papua Province, Indonesia. The average air temperature over the past five years ranged from 24.7°C to 28.2°C. The highest temperature was recorded in February 2020 (28.2°C), while the lowest temperature occurred in July 2019 (24.7°C). Humidity values ranged from 85% to 96%, with the highest humidity recorded in July 2020 (96%) and the lowest in March and April 2022 (85%).

Total rainfall varied significantly, ranging from 70.8 mm to 969.2 mm. The month with the highest rainfall was July 2020 (969.2 mm), while the lowest was November 2019 (70.8 mm). Solar intensity ranged from 57.9 W/m² to 133.1 W/m², with the highest intensity recorded in February 2018 (133.1 W/m²) and the lowest in July 2022 (57.9 W/m²). Wind speed remained relatively stable, ranging from 0.3 to 0.5 m/s, indicating that the wind in this region was relatively weak, with no significant changes throughout the year. The average air pressure ranged from 1005.4 mmBar to 1011.4 mmBar, with the highest pressure recorded in September 2019 (1011.4 mmBar) and the lowest in December 2018 (1005.4 mmBar).

The tailings deposition area at Tanggul Ganda consists of sand tailings produced from the mining of Ertsberg and Grasberg ores, originating from Ilaga intrusive rocks, as well as the remnants of valuable mineral rock crushing at the ore processing plant at the mile 74 highlands (Taberima 2009). The environmental division of PT. Freeport Indonesia carries out reclamation by planting various local plant species, with seedlings sourced from the natural forest (136°52'43.000" E 4°26'6.000" S) located 10 km from the reclamation site (136°53'59.006" E 4°29'57.503" S). The coordinates of the research locations in the natural forest across seven plots are: 136°52'43.000" E, 4°26'6.000" S and 136°52'39.000" E, 4°26'13.000" S and 136°52'42.276" E, 4°26'9.236" S and 136°52'41.317" E, 4°26'11.374" S and 136°52'45.461" E, 4°26'8.189" S and 136°52'44.719" E, 4°26'9.978" S and 136°52'43.890" E, 4°26'12.769" S. The coordinates of the research locations in the 21-year reclamation area across seven plots are: 136°53'59.006" E, 4°29'57.503" S and 136°53'59.006" E, 4°29'57.503" S and 136°53'59.200" E, 4°29'57.437" S and 136°53'59.913" E, 4°29'57.175" S and 136°54'0.043" E, 4°29'57.175" S and 136°53'59.395" E, 4°29'57.600" S and 136°53'59.072" E, 4°29'57.991" S. The coordinates of the research locations in the 12-year reclamation area across seven plots are: 136°53'59.976" E, 4°30'8.893" S and 136°53'59.716" E, 4°30'8.829" S and 136°53'59.846" E, 4°30'8.926" S and 136°53'58.173" E, 4°30'1.672" S and 136°53'57.851" E, 4°30'2.324" S and 136°53'59.856" E, 4°30'0.040" S and 136°53'59.985" E, 4°29'59.779" S. The coordinates of the research locations in the 10-year reclamation area across seven plots are: 136°53'48.743" E, 4°30'42.254" S and 136°53'48.647" E, 4°30'42.710" S and 136°53'48.291" E, 4°30'42.907" S and 136°53'48.647" E, 4°30'42.841" S and 136°53'48.096" E, 4°30'42.972" S and 136°53'48.194" E, 4°30'43.004" S and 136°53'48.387" E, 4°30'42.451" S. (Figure 1).

Sample collection procedure

The reclamation areas in this study were determined based on the duration of the reclamation process: 21 years (Level 1 was sampled from September 12 to 16, 2022, Level 2 (14 years) was sampled from September 26 to 29, 2022, and Level 3 (10 years) was sampled from October 10 to 12, 2022). Collembola were collected from all three reclamation levels following a 1000-meter transect. Main plots were established at every 142-meter interval, determined based on the conditions of the reclamation area, which was partially flooded. This resulted in a total of 7 main plots. Each main plot measured 20x20 m, and within each main plot, 5 sub-plots were arranged diagonally, each measuring 1x1 m as sample plots (Lu et al. 2018). Sampling was carried out six times, with three soil samples and three litter samples, resulting in a total of 30 sample plots for each main plot. Therefore, the total number of sample plots was 6 repetitions x 5 sub-plots x 7 main plots x 4 research locations, resulting in 840 sample plots. Soil samples were collected using an auger to a depth of 15 cm, while litter and soil samples were placed in 35x30 cm plastic bags. These litter and soil samples were then placed in modified Berlese funnels for Collembola extraction, which was carried out over 6 days (Haydar et al. 2019).

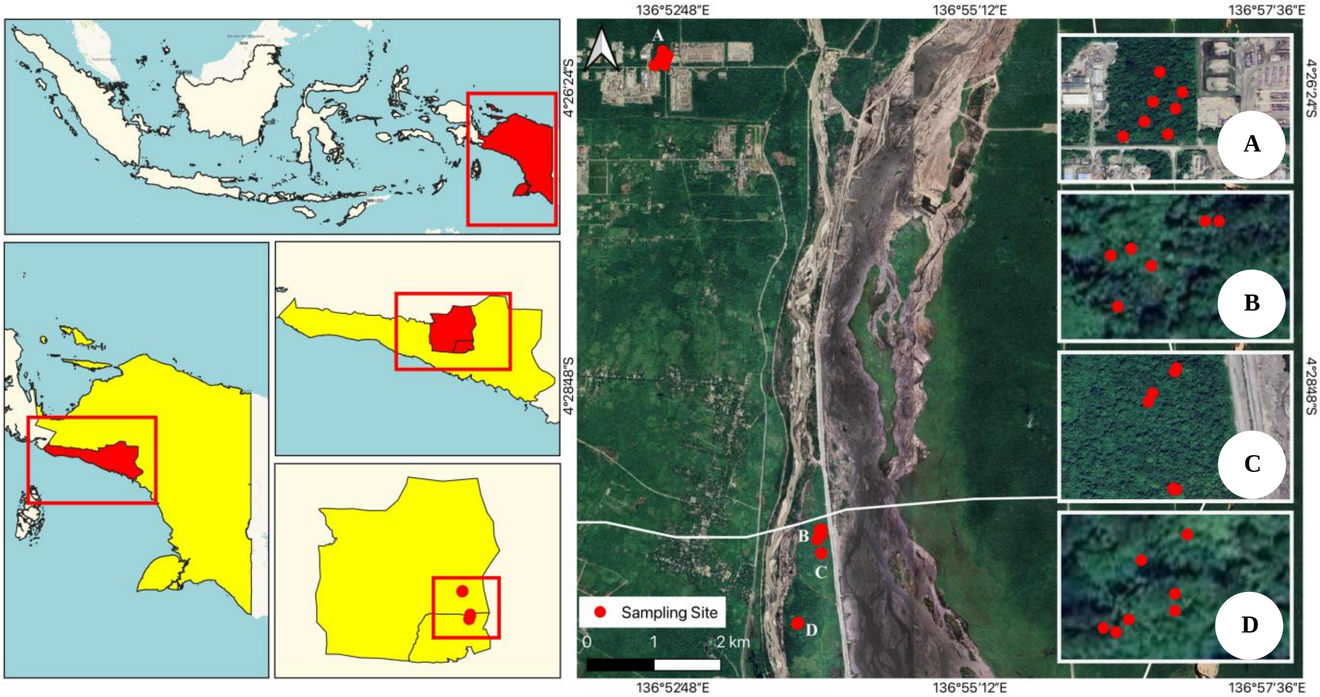

Figure 1. Research location in the reclamation area of PT. Freeport, Mimika, Papua, Indonesia. A. Natural forests, B-D. 21-year reclamation area

Collembola identification

The samples were then placed in vials containing 96% alcohol, labeled, and sent to the Basic Entomology Laboratory at the Faculty of Agriculture, Universitas Gadjah Mada, for identification at the family level. Order-level identification was based on morphological characteristics, such as body shape, thoracic segments, abdominal segments, and ocelli. Family-level identification was based on specific characteristics such as setae, body pigmentation, furcula, and tenaculum. Some specific ecomorphological traits of the body organs, such as the number of ocelli, antenna length, furca development, and the presence of setae and body pigmentation, were followed by the methods described, and the identification process used a morphospecies system to the family level, referring to standard identification keys (Bellinger et al. 2024). Collembola specimens transferred to tubes containing 96% alcohol were then picked up with tweezers and placed on slides for further examination. The prepared slides were then examined under a Leica M80 microscope, identified, and sorted by family and morphospecies within each family. The specimen was then placed under a Leica M80 microscope for identification. Ecological parameters such as diversity, dominance, species richness, evenness, and similarity were calculated using morphospecies. Identification was carried out up to the species level, but species names could not be determined, so species codes such as species 1, 2, 3, 4, and so on were used instead.

Data analysis

The diversity of Collembola was analyzed using several indices, including the Shannon-Wiener Diversity Index (H'), dominance Simpson Index (D), Margalef richness index (D), Sorensen Similarity Index (S), and Evenness index Pielou (J') (Magurran 2004). Significance tests for differences in Collembola abundance between reclamation areas and reference forests were performed using one-way ANOVA at a 5% significance level. Additionally, the characteristics of Collembola in each reclamation area were analyzed using Canonical Correspondence Analysis (CCA) to explore potential relationships between Collembola and environmental factors, such as soil chemical elements and metal content. This analysis was conducted using the "vegan" package in R Studio version 2023.06.0+421.

Shannon-Wiener Diversity Index (H') was calculated using the formula by McCarthy and Magurran (2004):

$$H' = -\sum_{i=1}^{s} pi \ln pi$$

Where,
H′ : Shannon-Wiener Diversity Index
pi : Abundance Index

Dominance was calculated using the Simpson Index by McCarthy and Magurran (2004):

$$D = \sum_{i=1}^{s} Pi^2$$

Where,
Pi : The ratio of each species
ni : The number of individuals of a given species
N : Total number of individuals across all species
Margalef Species Richness Index by Margalef (1958):

$$D = \frac{S-1}{\ln N}$$

Where,
S : The total number of species found
N : The total number of individuals in the sample

Sorensen Similarity Index by Lv et al. (2021):

$$S = \frac{2C}{A+B}$$

Where,
C : Number of species shared between two communities
A : Number of species in the first community
B : Number of species in the second community

Evenness was calculated using the Pielou Index by Hubálek (2000):

$$J' = \frac{H'}{\ln S}$$

Where,
J′ : Pielou Evenness Index
H′ : Shannon-Wiener Diversity Index
S : Number of species
ln(S) : Natural logarithm of the number of species

RESULTS AND DISCUSSION

Diversity, richness, and evenness of Collembola

The results of Collembola individual counts from the reclamation areas and the natural forest site are presented in Table 1. The calculation of the morphospecies diversity index using the Shannon-Wiener formula indicates that the natural forest and the 21-year reclamation area exhibit high levels of diversity. In comparison, the 14-year and 10-year reclamation areas are categorized as having moderate diversity. The values of the Shannon-Wiener Diversity Index, Pielou Evenness Index, Simpson Dominance Index, and Margalef Species Richness Index are presented in Table 2.

The 21-year reclamation area exhibited a higher number of individuals across both families and orders compared to the 14-year and 10-year reclamation areas, with morphospecies from the families Isotomidae (EI1) and Entomobryidae (EE3) being the most abundant. These findings are supported by Deharveng et al. (2020), who reported that the genus *Folsomides* from the family Isotomidae was dominant at their study sites, with two species, *F. centralis,* and *F. parvulus,* identified as codominant species in tropical regions and highly abundant in disturbed areas. Similarly, the family Isotomidae was also found to be dominant in other studies, including the species *Isotoma caerulea* and *F. parvulus* in Hungary (Harta et al. 2021). The family Entomobryoidea represents one of the most frequently encountered Collembola groups, particularly in disturbed areas, both in lowland and upland forests. This group accounts for approximately 15-25% of the total mesofauna population (George et al. 2017).

A community with a high number of species, indicating high diversity, generally also exhibits high species richness. However, calculations using the Margalef Species Richness Index revealed that species richness across all study sites, including natural forests and reclamation areas, was categorized as moderate, with index values ranging from 2 to 5. Although high diversity was recorded in both the natural forest and the 21-year reclamation area, species richness in these sites could not be classified as high. This is likely due to the fact that, despite the presence of many species, variation within the community remains relatively limited. Several morphospecies from the families Isotomidae, Sminthuridae, Neelidae, and Bourletiellidae were not found in the 21-year reclamation area. In comparison, in the natural forest area, certain morphospecies from the families Entomobryidae, Isotomidae, and Neelidae were absent.

Therefore, although species diversity in some reclamation areas has shown promising progress, environmental factors such as soil conditions and food availability continue to influence the growth and diversity of Collembola populations. More intensive reclamation efforts, along with continued monitoring of environmental changes in reclaimed areas, are necessary to support ecosystem recovery and enhance both diversity and species richness in future Collembola communities. Revegetation of mine tailings is one of the most cost-effective and efficient methods for reducing global environmental risks, especially when the rehabilitated areas are intended to develop into functional and sustainable ecosystems (Di Carlo et al. 2019). Collembola diversity is closely linked to adaptive capacity and food availability.

Differences in Collembola abundance between reclamation areas and natural forests, based on a one-way Kruskal-Wallis test, showed a significant difference (p-value: 0.0014). A post-hoc Dunn's test revealed a significant difference in the natural forest area. In contrast, no significant differences were found among area A (21-year reclamation), area B (14-year reclamation), and area C (10-year reclamation), all of which were labeled with the notation "a." In contrast, area D (natural forest) was significantly different and labeled with the notation "b." This indicates that Collembola abundance did not differ significantly among the reclamation areas from 21 to 10 years, but there was a significant difference when compared to the natural forest (Figure 2).

Species similarity of Collembola

The total number of Collembola individuals found across all research sites was 7,035. The 21-year-old reclamation area (Level 1) comprised 4 orders and 8 families, with a total of 2,109 individuals, higher than the 14-year-old reclamation area, with 1,158 individuals, and the 10-year-old reclamation area, with only 763 individuals. Meanwhile, the natural forest area, used as a control, consisted of 4 orders and 9 families, with a total of 3,005 individuals, representing the highest count among all study areas. The number of Collembola species is generally related to the number of families and orders, although not always directly. This means that a single family or order may contain many species, so species richness does not always reflect the number of families or orders.

Table 1. The number of Collembola individuals in reclaimed areas and natural forests

Family	Morphospecies	Reclamation area				Total
		21 years	14 Years	10 Years	Natural forests	
Entomobryomorpha						
Entomobryoidea	ENT1	61	86	148		295
	ENT2	63		58		121
	ENT3	112	55			167
	ENT4	69	86	38	92	285
	ENT5	51		29	29	109
	ENT6	33			34	67
	ENT7	92	37	17		146
	ENT8	31	26	84	41	182
	ENT9	112			86	198
	ENT10	37	21	52	78	188
Isotomidae	ISO1	121	96		100	317
	ISO2		74	41	45	160
	ISO3	105	89		41	235
	ISO4	96			62	158
	ISO5		62	47	60	169
	ISO6	105	85	62	126	378
	ISO7	89	62			151
	ISO8	110		56	51	217
Poduromorpha						
Hypogastruridae	HYP1	25	25		98	148
	HYP2	43			99	142
Neanuridae	NEA1	45	124		69	238
	NEA2	74	81		93	248
	NEA3	12			120	132
	NEA4	28			48	76
Onychiuridae	ONY1	93		21	96	210
	ONY2	142			40	182
	ONY3	61			90	151
	ONY4	27	18		49	94
	ONY5	41			57	98
Poduridae	POD1	41	28	14	69	152
	POD2	9			42	51
	POD3	6			33	39
	POD4	4			24	28
Symphypleona						
Bourletiellidae	BOU1				43	43
Sminthuridae	SMI1	75	46	25	172	318
	SMI2	86			236	322
	SMI3		57		194	251
Neelipleona						
Neelidae	NEE1	10		47	188	245
	NEE2				200	200
	NEE3				100	100
	NEE4			24		24
Total		**2109**	**1158**	**763**	**3005**	**7035**

Table 2. Diversity, evenness, dominance, and species richness values

Area reclamation	Shannon-Wiener Diversity Index	Pielou Evenness Index	Simpson Dominance Index	Margalef Species Richness Index
21 years	3.32	0.94	0.04	4.30
14 years	1.94	0.66	0.02	2.50
10 years	2.59	0.93	0.09	2.20
Natural forests	3.38	0.95	0.04	4.20

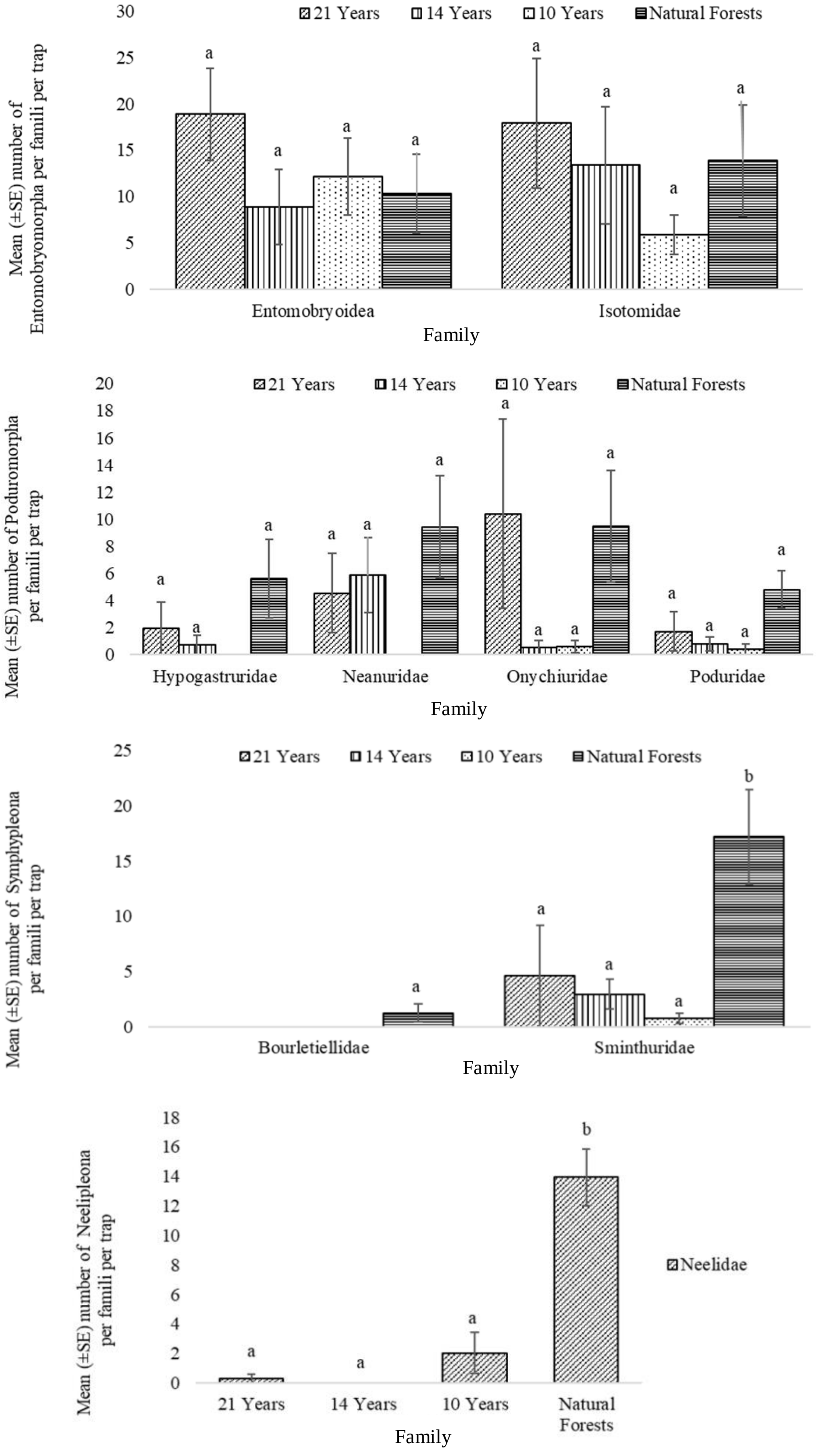

Figure 2. The number of each family in the reclamation area and the natural forest

The order Symphypleona, represented by the family Sminthuridae (morphospecies SMI2, SMI1, and SMI3), was most abundant in the natural forest area. In contrast, in the reclamation areas, the families Entomobryidae (morphospecies ENT3) and Isotomidae (morphospecies ISO1) from the order Entomobryomorpha dominated the 21-year-old reclamation area. In the 14-year-old reclamation area, Isotomidae was the most abundant family, followed by Entomobryidae. In comparison, in the 10-year-old reclamation area, Entomobryidae (morphospecies ENT1) was the dominant family, followed by Isotomidae and Neanuridae (morphospecies NEA1) from the order Poduromorpha. The abundance of Entomobryidae and Isotomidae families found in this study is consistent with the findings of Susanti et al. (2021), who reported that the family Isotomidae is prevalent in disturbed areas due to its strong colonizing ability and parthenogenetic reproductive strategy, which facilitates widespread distribution.

The high morphospecies Sorensen Similarity Index between the 21-year reclamation area and the natural forest (84%), as shown in Table 3, indicates that both locations share a highly similar morphospecies community. A total of seven morphospecies were absent in the 21-year reclamation area (BOU1, ISO2, ISO5, SMI3, NEE2, NEE3, NEE4), while six morphospecies were not found in the natural forest (NEE4, ISO7, ENT1, ENT2, ENT3, ENT7). Notably, morphospecies BOU1 was not recorded in any of the reclamation areas. In the 14-year reclamation area, 22 morphospecies were absent, including members of the families Bourletiellidae and Neelidae, whereas in the 10-year reclamation area, 25 morphospecies were not recorded, including members of Bourletiellidae, Hypogastruridae, and Neanuridae. This suggests that the reclamation process at the first level, which has been ongoing for 21 years, has been successful in developing a species composition that closely resembles that of the natural forest. However, some species are still absent, such as those from the family Bourletiellidae, and the number of individuals from the families Neelidae, Poduridae, and Sminthuridae remains lower. Meanwhile, the moderate similarity values between the second and third-level reclamation areas and the natural forest indicate that the species communities in these two reclamation areas are still in the early stages of ecological recovery.

The composition of Collembola communities and the environmental parameters that influence them

Table 4 presents the condition of soil nutrient content in the reclamation areas and natural forests. Ma et al. (2020) stated that in natural forests, vegetation plays a crucial role in determining the diversity and abundance of Collembola, particularly through the production of abundant and high-quality litter. Environmental recovery processes or changes, as well as the duration of reclamation, are among the key factors influencing species communities.

The lower Collembola diversity in the 14-year reclamation area (H': 1.94) compared to the other reclamation sites is likely due to the frequent inundation of the area during the rainy season, which affects food availability and population growth of Collembola. This finding is consistent with Krediet et al.'s (2023) statement that the composition of Collembola communities undergoes noticeable changes with increasing or decreasing flood intensity, with the most significant shifts occurring in areas that are frequently flooded.

Meanwhile, the 21-year-old reclamation area has shown developments approaching the characteristics of natural forest, indicating its growing capacity to support natural ecosystem development. According to Winck et al. (2017), natural forests are known to accumulate deposits from various plant and animal materials continuously. The combination of these materials, along with the balanced environmental conditions of the forest, contributes to the high biomass and microbial activity in the resulting residues.

In addition, the differences in values between the 21-year area and the two younger reclamation areas are likely due to the longer duration of reclamation, which aligns with the findings of Pollierer and Scheu (2017), who stated that the length of management time clearly influences Collembola biomass and community structure. Multiple factors influence soil fertility; therefore, this study employed Canonical Correspondence Analysis (CCA) to examine the relationship between soil fertility parameters and the presence of Collembola. The results revealed correlations between Collembola distribution and soil fertility variables, as illustrated in Figure 3. Blue arrows represent environmental variables such as pH, moisture, Soil Organic Matter (SOM), and others; the direction of the arrows indicates the correlation with species (Collembola families).

Table 3. Species Sorensen Similarity Index between reclamation areas and natural forest

Area reclamation	S	Category
21 years x 14 years	60%	Moderate
14 years x 10 years	57%	Moderate
10 years x 21 years	52%	Moderate
Natural Forest x 21 years	84%	High
Natural Forest x 14 years	56%	Moderate
Natural Forest x 10 years	47%	Moderate

Table 4. Soil chemical elements in the reclamation area and the natural forest

Area	Location	N total (%)	C (%)	SOM (%)	Moisture content (%)	P total (%)	Available K (mg)	CEC (cmol)	pH	Total K (%)
21 years	Plot 1	0.30	1.37	2.36	0.60	0.05	116	8.45	7.00	0.60
	Plot 4	0.11	2.07	3.57	5.60	0.05	121	11.65	4.40	0.20
	Plot 7	0.02	1.19	2.05	0.80	0.06	25	3.93	5.10	0.30
14 years	Plot 1	0.03	1.42	2.45	0.06	0.08	23	2.82	5.20	0.30
	Plot 4	0.02	1.44	2.49	0.06	0.06	101	1.91	6.00	0.50
	Plot 7	0.03	1.34	2.30	0.06	0.04	95	8.85	6.10	0.30
10 years	Plot 1	0.03	1.21	2.08	0.60	0.03	66	6.64	6.30	0.20
	Plot 4	0.01	1.18	2.03	0.20	0.02	70	1.20	5.80	0.40
	Plot 7	0.04	1.53	2.65	0.80	0.03	29	8.67	5.10	0.50
Natural forests	Plot 1	0.04	1.54	2.66	0.60	0.05	22	4.63	4.80	0.30
	Plot 5	0.15	2.88	4.96	8.00	0.02	24	8.26	4.80	0.30
	Plot 6	0.12	2.31	3.98	19	0.05	92	8.02	4.30	0.30

Two Collembola families showed different associations with environmental variables. The Onychiuridae family, positioned near Total Nitrogen (Ntot), was more abundant in areas with high nitrogen content, a condition observed in sample plot A1. In contrast, in plot B7 of the 14-year reclamation area, the Entomobryoidea family appeared to be more influenced by soil pH. The Bourletiellidae and Neelidae families exhibited similar responses to moisture levels, with a dominant presence in the natural forest control area (plots D1, D4, and D7). A study by Dewi et al. (2024) on post-rehabilitation land showed that the Sminthuridae family was responsive to high soil moisture conditions; however, in this study, Bourletiellidae and Neelidae demonstrated greater responsiveness to moisture than Sminthuridae. Total phosphorus content was associated with the presence of Isotomidae, which was more dominantly found in the 14-year reclamation area (plots B1, B4). The response of Isotomidae to phosphorus is consistent with previous findings suggesting that phosphorus is a key driver of Collembola communities (Harta et al. 2021). The positive relationship between Collembola and soil phosphorus is linked to an increased abundance of other organisms that can serve as alternative food sources for Collembola, such as saprotrophic fungi (Zhang et al. 2023).

The Poduridae family appeared to be associated with soil organic matter and carbon content, as indicated by its position close to the vectors for SOM and C (Carbon) in the CCA biplot. The potential linkage between Collembola and soil organic matter and carbon can be explained by the role of organic matter as a key indicator of soil quality, which significantly influences the reclamation process (Gao et al. 2018). Reclamation activities may alter soil carbon content by affecting the redistribution of macronutrients into biomass, nutrient cycling, and storage in soil, along with the activity of soil biota, including Collembola, which play an important role in supporting these processes (Harta et al. 2021). The Entomobryidae family showed an association with soil pH conditions. Improvements in soil quality resulting from reclamation efforts can be observed through enhanced soil aeration. Improved soil aeration influences changes in soil pH (Sahu et al. 2022). This study demonstrated that the pH levels in post-tailings reclamation areas were higher compared to those in natural forests, although all sites were still classified as acidic soils. The pH conditions across all study areas remained within the tolerance range for Collembola, which spans from pH 2 to 9 (de Boer et al. 2010).

The Onychiuridae family showed correlations with both Cation Exchange Capacity (CEC) and Ntot, although its placement on the biplot was more closely aligned with the CEC vector. Soil cation exchange capacity is a commonly used indicator for assessing soil fertility, particularly in post-mining landscapes. The findings of this study suggest that several Collembola families are associated with CEC values, consistent with previous research indicating that improving soil conditions can enhance CEC. Increased soil CEC capacity is often accompanied by increased diversity and species richness of Collembola (Chairunnisa et al. 2022).

The soil conditions in the reclamation areas were exposed to heavy metals such as mercury (Hg), copper (Cu), lead (Pb), and arsenic (As), which were transported through material flow, as presented in Table 4. The presence of Collembola in the reclamation areas is associated with metal content, which can be analyzed using Canonical Correspondence Analysis (CCA). The CCA biplot (Figure 4) illustrates the relationship between environmental variables (indicated by blue arrows, such as Hg, Pb, and Cu) and the distribution of organism species (represented in red text). Most Collembola families, such as Isotomidae, Poduridae, Entomobryidae, and Neanuridae, are located near the center of the vector arrows, suggesting a weaker association with metal elements when present in low concentrations. However, a stronger relationship is observed with copper (Cu), particularly for the Neelidae family, which is positioned further from the plot center.

The CCA analysis indicates that the Neanuridae and Entomobryidae groups tend to be associated with positive values on CCA1, whereas Neelidae is more closely linked to negative values on CCA1. Meanwhile, positive values on CCA2 demonstrate a stronger relationship with mercury (Hg), particularly for the Hypogastruridae and Sminthuridae families. In contrast, negative values on CCA2 suggest that Neelidae is more influenced by copper (Cu). Additionally, lead (Pb) in the reclamation areas affects the Entomobryidae and Poduridae families, as indicated by their proximity to the Pb vector arrow. This relationship is most prominent in the 21-year-old reclamation area compared to the younger sites. Soil Pb content may impact Collembola both directly and indirectly, with previous studies showing that soils with high Pb concentrations tend to be inhabited by Collembola species with a greater number of ocelli. In other words, areas with high Pb contamination may exhibit higher taxonomic diversity but lower functional diversity (Vincent et al. 2018).

On the other hand, Neanuridae showed a notable response to Hg, especially in the 14-year-old reclamation area, where Hg concentrations were lower than in the 21-year-old area. The reduction in Hg levels in the 14-year-old site corresponds with an increase in Neanuridae abundance, which is consistent with findings from the post-mining areas in Poboya. In that region, Neanuridae were more abundant in areas farther from the mining centers, where Hg contamination levels were lower (Hasriyanty et al. 2018). Despite the 21-year-old reclamation site being the oldest, Hg contamination remains high due to illegal mining activities (Figure 5.A), where miners have built temporary settlements (Figure 5.D) and use mercury (Hg) in the amalgamation process (Figures 5.B and 5.C).

Table 4. Metal contaminant elements in the three reclamation areas

Reclamation level	Unit	Hg	Pb	Cu
21 years	ppm	0.76	25.00	222
14 years	ppm	0.50	23.33	400
10 years	ppm	0.26	25.00	422

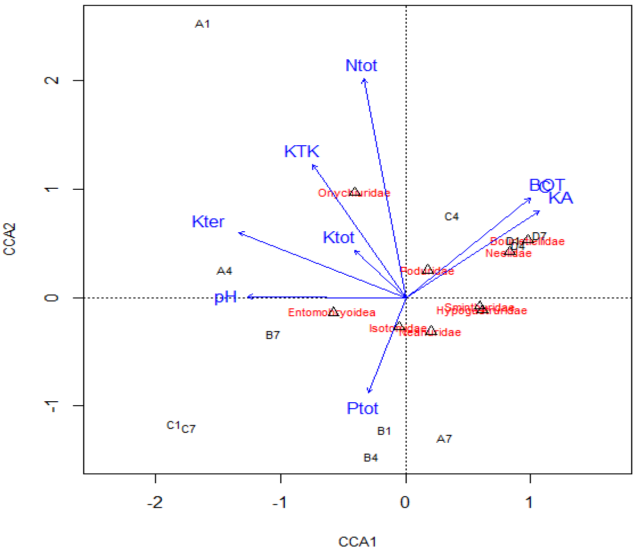

Figure 3. CCA biplot results of Collembola presence in relation to soil chemical properties. Explanation: Ntot: Total Nitrogen; BOT: Soil Organic Matter; C: Carbon; KA: Moisture Content; Ptot: Total Phosphorus; pH: Soil pH; Kter: Available Potassium; KTK: Cation Exchange Capacity; A1, A4, A7: 21-year reclamation; B1, B4, B7: 14-year reclamation; C1, C4, C7: 10-year reclamation; D1, D4, D7: Natural Forest

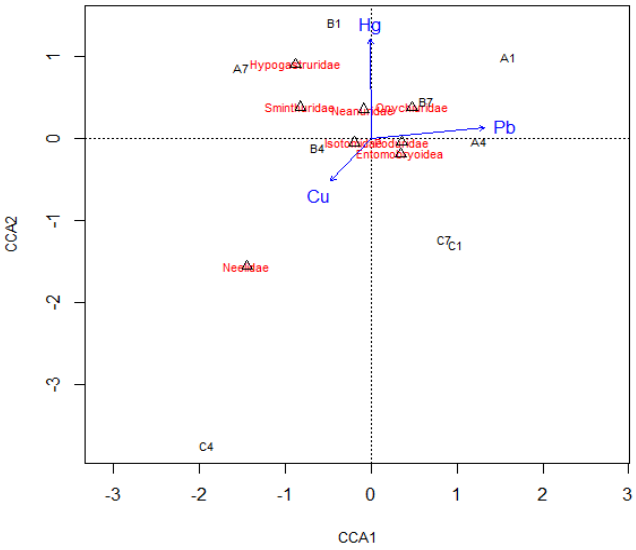

Figure 4. CCA biplot results showing the relationship between the presence of Collembola and metal content. Explanation: Hg: Merkuri; Cu: Tembaga; Pb: Timbal; A1, A4, A7: 21-year reclamation; B1, B4, B7: 14-year reclamation; C1, C4, C7: 10-year reclamation

Figure 5. The 21-year-old reclamation area and illegal mining activities at the camp

The use of mercury without proper waste treatment systems has led to long-term pollution accumulation, contaminating both the soil and water bodies around the reclamation area (Figure 5). The families Isotomidae and Neelidae exhibited responses to copper (Cu) content, with Isotomidae showing a closer association. Although Neelidae was positioned farther away, its orientation remained aligned with the Cu vector arrow, indicating a potential relationship with the element. The association between Collembola and Cu was more evident in the 14-year-old reclamation area compared to other areas. The proximity of Isotomidae to the Cu vector arrow suggests an interaction between the two. Collembola possess the ability to regulate metal concentrations within their bodies. The species *Lobella sokamensis* is known to feed on dead or unhealthy earthworms. During the excretion process, it was observed that the bodies of these earthworms contained heavy metals such as cadmium (Cd), copper (Cu), antimony (Sb), and zinc (Zn), likely originating from the bioaccumulation process by *L. sokamensis* (Youn et al. 2013).

The presence of Collembola, as measured by species diversity and richness, increased with the length of the reclamation period. The highest diversity was found in the natural forest and the 21-year-old reclamation area, indicating that longer reclamation periods can support more stable ecosystem recovery and enhance Collembola diversity. Additionally, soil fertility parameters such as organic matter, carbon, and phosphorus were shown to play significant roles in supporting the presence of Collembola. On the other hand, three types of metal contaminants demonstrated specific potential relationships with particular Collembola families. Certain Collembola families exhibited preferences for specific environmental conditions. For instance, the Isotomidae family tended to be more tolerant of disturbed soils, while the Neanuridae family was more sensitive to heavy metal contamination. These findings highlight the importance of adopting sustainable reclamation approaches and underscore the need for continuous monitoring and collaboration with relevant stakeholders to control illegal mining activities, ensuring that reclamation efforts effectively support biodiversity recovery in post-mining ecosystems.

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