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Enhancing Soil Aggregation and Water Retention by Applying Kaolinite Clay to Post-Tin-Mined Land on Belitung Island, Indonesia

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ABSTRACT

Post-mining sandy soils have low water retention, which causes soil particle separation and persistent soil erosion. Although organic matter is commonly used for soil restoration, it is lightweight, washes away during heavy rain, and decomposes under strong sunlight. The high potential for extreme rainfall events in tropical regions poses significant challenges to restoration projects. Therefore, we investigated the impact of kaolinite clay particles on enhancing soil stability in post-mining sandy soils. Soil samples were collected from three sites representing different succession stages of post-mined land (0, 1, and 6 years since mining cessation) and an adjacent natural forest as the reference site on Belitung Island, Indonesia. Soil samples were treated with 1% or 5% kaolinite or left untreated (control) and incubated at 34°C to mimic the local conditions of the study area. The samples were then analyzed to determine the soil aggregate distribution, water holding capacity, and soil erodibility, and SEM imaging was performed to examine the soil particle morphology. The results revealed an increasing trend in the silt-sized aggregate content and a 2%–5% increase in water retention in the 6-year soils relative to the untreated soils. The highest water retention was observed in the 6-year post-mining soil sample. Kaolinite amendment significantly reduced soil erodibility by 40%–50% compared to the untreated soils, even in the early restoration period (0–1 year post-mining). Kaolinite improved soil aggregation and water retention in post-mining sandy soils while reducing soil erodibility—highlighting its potential for accelerating land restoration in mining-affected areas.

1 | Introduction

Soil conservation plays a crucial role in preserving Nature's Contributions to People (NCP). Protecting half of the global land area could sustain 90% of the current NCP levels (Neugarten et al. 2024). Additionally, to maintain global carbon storage and moisture recycling, at least 44% of the land area must be conserved (Chaplin-Kramer et al. 2023). Although soil conservation efforts have been made, soil conservation services are increasingly challenged by factors such as terrain, climate, and land-cover changes (An et al. 2022). In recent decades, changes to approximately 722 Mha of global land cover have occurred (Hu et al. 2021), with inadequate land-use practices, including deforestation and mining activities, leading to intensified soil erosion in tropical regions (Wantzen and Mol 2013).

Soil erosion is a growing global issue that is primarily driven by climate change (Borrelli et al. 2020; Xiong and Leng 2024). Global

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warming has led to a 2.1% increase in global soil erosion (Ma et al. 2021). Changes in land use over the decades have further contributed to this trend (Jien et al. 2023). By the end of the current century, soil erosion rates are projected to increase by 14.2% (Eekhout and de Vente 2022), with a current mean global erosion rate of 5.78 $t\,ha^{-1}\,year^{-1}$ (Li, Xiong, et al. 2024). Over the last decade, the area affected by severe erosion has expanded by 19.49% (He et al. 2024). Regions with annual rainfall exceeding 1000 mm are expected to experience more severe soil erosion than drier areas, necessitating enhanced soil conservation measures (Ebabu et al. 2022). Precipitation is strongly linked to water erosion, which intensifies as temperatures increase (Dou et al. 2022). Moreover, anthropogenic activities such as deforestation expose bare lands to soil loss ranging from 10.6 to 109.2 $t\,ha^{-1}\,year^{-1}$ (Xiong et al. 2019).

To mitigate soil erosion and adapt to future climatic challenges, more extensive soil management strategies are needed (Chapman et al. 2021). Soil conservation techniques can reduce annual soil losses by 84% and runoff by 53% (Xiong et al. 2018). Organic matter application has successfully minimized soil erosion across various spatial scales (Gholami et al. 2019), and physical treatments, such as contour management and artificial macropores, can enhance soil structural stability and soil organic carbon storage (Ghosh et al. 2021; Mori et al. 2013, 2014). Vegetation roots help bind soil particles, which, in turn, decrease erosion (Li, Xie, et al. 2024; Pandey et al. 2024). A combination of physical and biological approaches can decrease soil and water loss while increasing the soil water-holding capacity (Ghassemi-Golezani and Farhangi-Abriz 2022; Huang et al. 2022; Verheijen et al. 2019).

The collapse of soil aggregates is a primary cause of soil degradation. Stable aggregates enhance soil resistance to erosion and help maintain the soil structure after rainfall (Li et al. 2022; Regelink et al. 2015). Factors that contribute to soil aggregate collapse include excessive mechanization, organic matter depletion due to accelerated decomposition under elevated temperatures, degradation of surface litter under intense sunlight, heavy rainfall erosion, and soil washing during mining activities (Han et al. 2024; Malongweni and van Tol 2024; Zhang et al. 2024). This study focuses on Indonesia, where mining activities encompass all these conditions, resulting in the collapse of soil aggregates and loss of clay-silt-sized particles from the soil matrix.

The collapse of soil aggregates diminishes soil water retention or water-holding capacity, thus causing fine particles to be washed away. This adversely affects plant establishment and prevents the accumulation of soil organic matter, which is essential for soil fertility and stability (Cui et al. 2024). Soil porosity is crucial, with coarse pores facilitating permeability and rapid drainage, and fine pores retaining moisture between rainfall events (Geroy et al. 2011; Li, Guo, and Lin 2024). The loss of fine particles due to erosion significantly impairs soil water retention and hinders vegetation establishment and recovery (Kumar et al. 2023). Therefore, the loss of either aggregates or fine particles affects water retention.

Restoring degraded land requires the reintroduction of fine particles that improve soil structure and function. The application of clay may stabilize eroded sandy soil ecosystems (Pi et al. 2020). In Belitung Island, Indonesia, the soil contains many kaolinite clay layers (Estiaty and dan Fatimah 2014) that can be used for soil restoration. Moreover, kaolinite can be incorporated as a soil ameliorant in sandy tailings during tin mining disposal (Anda et al. 2022). Kaolinite is easy to find in the area surrounding post-tin mining land. Clay mineral amendments can alter soil physicochemical properties, such as pH, fertility, nutrient availability, and soil organic carbon retention, and can promote microaggregate formation and microbial activity (Tahir and Marschner 2017; Ye et al. 2019; Yu et al. 2022).

Recent studies have identified shifts in microbial community composition as important indicators of ecological restoration progress (Putra et al. 2024). Microbial activity in these soils is strongly influenced by decreases in soil acidity and cation exchange capacity (Armanisa et al. 2024). These constraints are largely attributable to the legacy of tin mining, which has resulted in soils with minimal vegetation cover, poor structural stability, limited water infiltration, and depleted nutrient stocks (Putra et al. 2017). In addition, the loss of fine particles during mining has further reduced the water-holding capacity of the soil, although revegetation initiatives have been shown to gradually improve these properties (Oktavia et al. 2015). The accumulation of soil organic matter during revegetation is particularly critical, and its persistence can be enhanced through interactions with reactive clay mineral surfaces, which bind organic molecules and contribute to the long-term stabilization of soil fertility and resilience (Carvalho et al. 2023).

Despite these insights, a critical challenge remains in the early stages of post-mining restoration, when the soil lacks vegetation cover and, therefore, exhibits a very limited water-holding capacity. Conventional remediation methods, such as the addition of organic matter, often prove ineffective under tropical conditions because heavy rainfall accelerates leaching and prevents long-term water retention. This underscores the need for alternative strategies that can enhance soil structure and improve water retention, even before vegetation is fully established. Given the natural abundance of kaolinite in Belitung's post-mining landscapes, clay amendments may provide a solution. However, the potential of kaolinite to promote microaggregate formation, improve water-holding capacity, and reduce erosion risk in tin-mined soils is poorly understood.

To address this knowledge gap, this study investigated the application of kaolinite across different post-mining stages to evaluate its effectiveness in restoring soil aggregation, water retention, and erosion resistance. Soil samples treated with 1% and 5% kaolinite were analyzed to determine the soil aggregate distribution, water holding capacity, and soil erodibility, and SEM imaging was performed to examine the soil particle morphology. These findings provide insights into the use of kaolinite for soil rehabilitation in tropical post-tin-mined landscapes.

2 | Materials and Methods

2.1 | Soil Sampling

Soil samples were collected from a post-tin-mined area in Selinsing Village, Gantung Sub-district, East Belitung Regency, Bangka Belitung Province, Indonesia. The soil sampling sites were divided into the following four categories: 0Y, 0 years since

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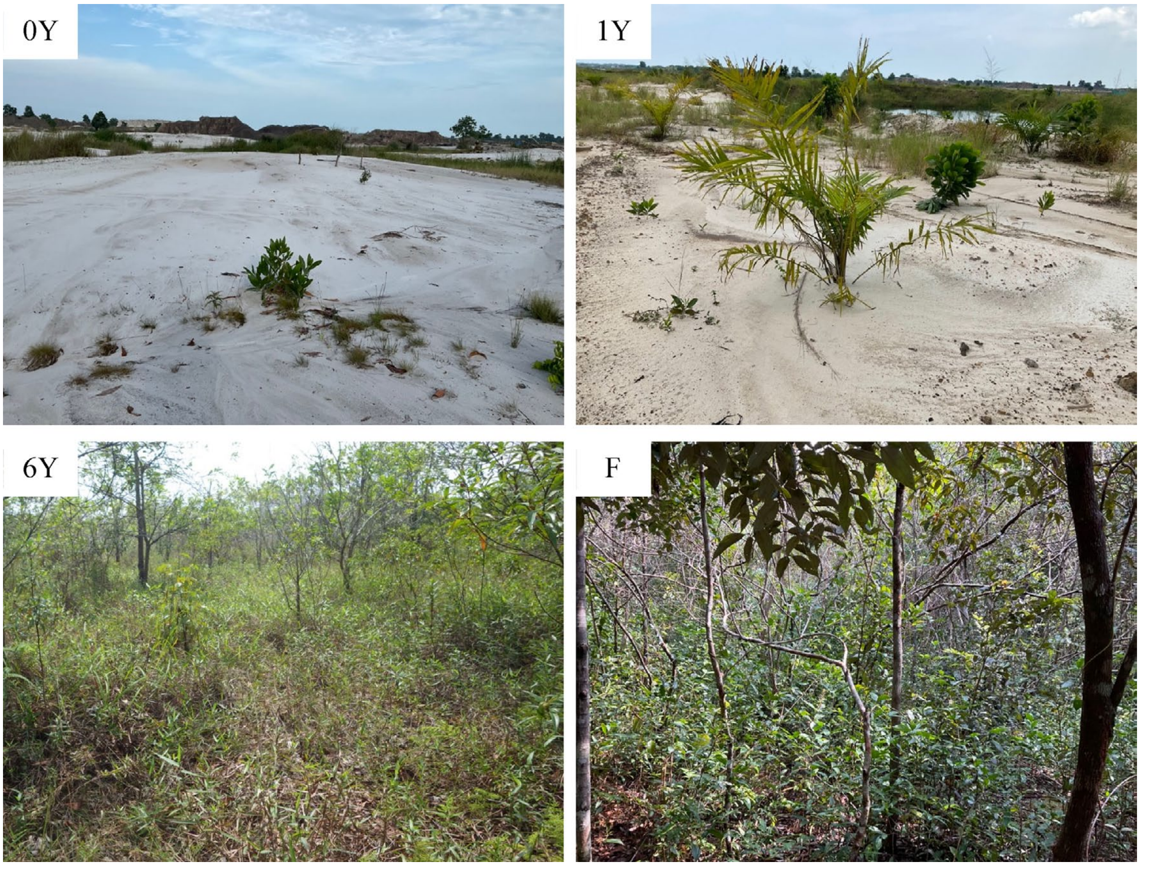

FIGURE 1 | Soil cover of sampling sites. Y, years since mining was stopped; F, forest as the reference site. [Colour figure can be viewed at wileyonlinelibrary.com]

mining was stopped (Site 0Y; 2° 55′ 42.10″ S, 108° 12′ 39.90″ E, elevation: 5 m asl), the land was not reclaimed, and a limited amount of grass was established on white sandy soils; 1Y, 1 year since mining was stopped (Site 1Y; 2° 55′ 50.30″ S, 108° 12′ 18.70″ E, elevation: 7 m asl.), the land was already reclaimed, but most of the landscape was still dominated by white sandy soils; 6Y, 6 years since mining was stopped (Site 6Y; 2° 55′ 47.00″ S, 108° 11′ 40.00″ E, elevation: 15 m asl), the land was already reclaimed, some dense shrubs and trees were established, but white sandy soils were still dominant; and F, a reference site in the nearby tropical heath forest (Site F; 2° 55′ 40.00″ S, 108° 11′ 39.00″ E, elevation: 25 m asl). Samples were obtained from soil depths of 0, 10, and 30 cm. Site 1Y was reclaimed by planting palm and *Acacia* trees, Site 6Y was reclaimed through the natural occurrence of spontaneous shrubs and by planting *Acacia* trees, and Site F was covered by heath forest vegetation typical of Belitung Province (Figure 1). During the sampling period, 200–300 mm of rainfall occurred each month at the study sites (BMKG 2022). Soil temperatures ranged from 27.5°C to 34.3°C across all locations, depending on the weather conditions and sampling time. The samples were stored in a refrigerator at 4.0°C.

2.2 | Experimental Setup

Soil organic matter is used in soil remediation processes; however, in this experiment, we used kaolinite (Hayashi Pure Chemical Ind. Ltd., Japan) to enhance the soil aggregation process rather than soil organic matter, which is composed of plant residues. Kaolinite can be an effective early stage amendment for post-mining soil remediation because its stability and resistance to rapid decomposition under high temperatures and intense sunlight allow it to improve the soil structure and water retention capacity. In this experiment, we used commercially available kaolinite rather than sourcing it directly from Belitung Island to minimize uncertainties associated with local material variability. Although compositional differences may exist, the findings are expected to be broadly comparable to the effects of locally available kaolinite, thus providing insights relevant to practical soil remediation in post-tin-mining landscapes.

We subjected air-dried tin-mined soils from 0Y, 1Y, 6Y, and F to the following three treatments: bare soil (control), 1% kaolinite application, and 5% kaolinite application. Each treatment was replicated three times. For each treatment, soil samples were water-saturated in a 50 cm^3 soil cylinder. The bulk density ($g\,cm^{-3}$) of each cylinder was adjusted to the mean field bulk density according to soil depth, that is, 1.50 for 0Y, 1.57 for 1Y, 1.78 for 6Y, and 1.49 for F soils. After preparation, the samples were incubated independently at 34°C to mimic field conditions until the soil dried. The incubation duration may vary among samples and will be reported in the Results section. The sample weights were measured daily.

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2.3 | Analysis of Soil Physical Properties

Initial data on soil particle size distribution, soil moisture content, TC/TN, acidity, and bulk density were obtained from the soil samples from sites 0Y, 1Y, 6Y, and F. Soil water content was measured in the laboratory using the gravitational method (Hillel 1998; Dane and Topp 2002). The soil particle distribution was analyzed using a laser diffraction particle size analyzer (SALD 3100; Shimadzu Corporation, Kyoto, Japan) and classified as coarse sand (0.2–2.0 mm), fine sand (0.02–0.2 mm), silt (0.002–0.02 mm), and clay (< 0.002 mm) according to the International Society of Soil Science (Jury and Horton 2004).

After the incubation process, wet sieving was performed in series by gently shaking the sieve under water, and the results were used to measure the soil aggregate sizes of 0.053, 0.075, 0.106, 0.25, 0.85, and 2 mm (Liu et al. 2021; Ngo et al. 2024; Rieke et al. 2022).

An analytical scanning electron microscope (SEM; JSM-6010LA, JEOL, Tokyo, Japan) was used in vacuum mode to determine the soil aggregate size. After the soil particles were air-dried, they were attached to conductive adhesive tape to prevent scattering under vacuum. For this measurement, gold coating was not used, and the soil particles were imaged under low-vacuum conditions to prevent them from becoming electrified.

The soil samples were saturated from the bottom in a water bath, and the soil water retention time was monitored by recording the weight of the samples daily during the incubation period until the soil was dry (less than 5% water content). The water retention time was measured to understand the water retention characteristics of the soil with respect to evaporation.

The soil water retention curve was determined using the pinhole multistep centrifuge outflow method (Bui and Mori 2021). After saturation, the samples were centrifuged for 30 min at various velocities (100, 300, 500, 800, 1000, and 1500 rpm), which were equivalent to 13, 121, 337, 862, 1346, and 3029 cm H_2O, respectively. Subsequently, the samples were oven-dried at 105°C for 24 h. The soil water retention curve was measured to understand the water holding properties of the soil with respect to the suction pressure. As the pore space and suction pressure are closely related by capillary force theory, the associated particle size can be estimated.

Soil erodibility (*K*-factor) indicates the extent to which the soil can be eroded by surface flow. The following equation proposed by Wischmeier and Smith (1978) was used to estimate the K-factor:

$$K = 2.76 \times 10^{-7} M^{1.14} (12 - \mathrm{OM}) + 0.0043\,(s - 2) + 0.0033\,(p - 3),$$

where M is defined as the textural factor and is obtained by multiplying two terms: $(m_{\mathrm{silt}} + m_{\mathrm{vfs}})$ and $(100—m_c)$. In this formula, m_c indicates the proportion of the clay fraction, m_{silt} indicates the proportion of the silt fraction, and m_{vfs} indicates the proportion of the very fine sand fraction. In addition, OM refers to the percentage of organic matter; s represents soil structure, with $s = 1$ corresponding to very fine granular, $s = 2$ to fine granular, $s = 3$ to medium or coarse granular, and $s = 4$ to blocky, platy, or massive types; and p represents permeability, with $p = 1$ (>146.4 cm/day, very fast), $p = 2$ (48.72–146.4 cm/day, moderately fast), $p = 3$ (12.24–48.72 cm/day, moderate), $p = 4$ (4.8–12.24 cm/day, moderately low), $p = 5$ (2.4–4.8 cm/day, slow), and $p = 6$ (< 2.4 cm/day, very slow).

2.4 | Data Analyses

Statistical analyses of the data were performed using SPSS (IBM, Chicago, IL, USA) and RStudio 2023.06.0 Build 421 (RStudio, Boston, MA, USA), and univariate analyses of variations in soil properties between treatments and comparisons between the treatments and forest reference site were performed in SPSS. RStudio was used to understand the direction and relationship of the soil property data from the principal component analysis (PCA). Data on soil aggregate size distribution, soil water retention time, and soil water retention curve were selected for PCA to distinguish the soil treatments and confirm the impact of kaolinite on soil water retention and aggregate formation.

3 | Results

3.1 | Initial Soil Particle Distribution and Soil Water Content

Tin mining on Belitung Island has resulted in the complete loss of fine particles (silt and clay) from soils at depths of up to 35 cm, compared to the reference forest sites (Table 1). The mined soils were dominated by coarse sand, which accounted for 83%–99% of the total mass. The soil acidity (pH) ranged from 3.7 to 4.8. The volumetric water content increased as it neared the reference value. The field soil water content at the 6-year site was higher than that at the 0-year and 1-year sites.

3.2 | Soil Aggregate Size Distribution

Aggregates were classified by size as follows: large macroaggregates (> 2000 μm), medium macroaggregates (1000–2000 μm), small macroaggregates (250–1000 μm), microaggregates (53–250 μm), and silt and clay (< 53 μm) (Guest et al. 2022). The < 53 μm category includes very small microaggregates (Totsche et al. 2018). As clay particles are < 2 mm, this study describes the < 53 μm category as "silt-sized aggregates."

Kaolinite application to post-mined soils first promoted an increase in silt-sized aggregates (< 53 μm), which increased proportionally to the soil restoration stages (Figure 2). At 0Y, an increase in 250-μm aggregates was also observed with 5% kaolinite addition. At 1Y, increases in 250- and 850-μm aggregates were observed with both 1% and 5% additions. At 6Y, increases in 106- and 250-μm aggregates were observed. Although forest-like aggregates exceeding 1000 μm were not observed in any case, increases were seen in small macroaggregates (250–1000 μm), microaggregates (53–250 μm), and silt-sized aggregates (< 53 μm).

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TABLE 1 | Soil Properties at Study Sites.

Site	Soil depth (cm)	Coarse sand (%)	Fine sand (%)	Silt (%)	Clay (%)	Bulk density	Water content (%)	Soil carbon (%)	Soil nitrogen (%)
0Y	0–5	84.87 ± 6.14	15.13 ± 6.14	0	0	1.46 ± 0.13	20.37 ± 7.09	0.05 ± 0.01	0.008 ± 0.0002
	10–15	88.98 ± 1.87	11.02 ± 1.87	0	0	1.53 ± 0.03	15.49 ± 1.87	0.06 ± 0.03	0.009 ± 0.0007
	30–35	91.34 ± 1.62	8.66 ± 1.62	0	0	1.51 ± 0.06	19.89 ± 2.36	0.04 ± 0.02	0.008 ± 0.0004
1Y	0–5	88.5 ± 3.50	11.48 ± 3.49	0.02 ± 0.03	0	1.52 ± 0.06	11.41 ± 0.55	0.09 ± 0.04	0.006 ± 0.002
	10–15	94.7 ± 2.22	5.3 ± 2.22	0	0	1.57 ± 0.05	13.57 ± 1.31	0.05 ± 0.02	0.003 ± 0.001
	30–35	90.25 ± 1.37	9.75 ± 1.37	0	0	1.62 ± 0.07	13 ± 3.11	0.04 ± 0.01	0.003 ± 0.001
6Y	0–5	83.43 ± 28.71	16.57 ± 28.71	0	0	1.73 ± 0.27	28.61 ± 7.01	0.10 ± 0.06	0.010 ± 0.004
	10–15	99.74 ± 0.44	0.26 ± 0.44	0	0	1.77 ± 0.29	33.18 ± 2.22	0.17 ± 0.15	0.015 ± 0.007
	30–35	93.14 ± 7.73	6.86 ± 7.73	0	0	1.83 ± 0.17	26.69 ± 13.36	0.09 ± 0.06	0.010 ± 0.001
F	0–5	45.22 ± 50.17	20.93 ± 18.91	20.82 ± 20.04	13.03 ± 11.49	1.49 ± 0.29	37.37 ± 3.12	1.44 ± 1.03	0.087 ± 0.047
	10–15	0.25 ± 0.85	27.94 ± 4.20	42.54 ± 4.71	29.27 ± 9.18	1.54 ± 0.29	32.35 ± 5.60	0.96 ± 0.24	0.070 ± 0.026
	30–35	11.88 ± 20.13	54.94 ± 9.08	10.89 ± 11.69	22.3 ± 14.83	1.44 ± 0.27	31.06 ± 5.90	0.40 ± 0.18	0.045 ± 0.006

The SEM images (Figure 3) confirmed the increased abundance of silt-sized aggregates owing to kaolinite application in all soils representing different restoration stages. For both the 0Y and 1Y samples, the quantity of silt-sized aggregates was higher in the 1% kaolinite treatment than in the 0% treatment, and it further increased in the 5% treatment compared to that in the 1% treatment. Kaolinite is a clay with particles less than 2 μm in size; therefore, it cannot be observed at this magnification. Therefore, all identified particles were sand particles or aggregates. Examples of silt-sized aggregates (0Y, 1Y) and micro-aggregates (6Y) are circled in red.

SEM revealed larger soil aggregates in the 6Y soil samples. However, the particle size was smaller than those of the 0Y and 1Y soil samples because of the high silt levels at this site (Putra et al. 2024). Fine sand particles dominated the 0Y and 1Y soils. In contrast, silt- or sand-sized aggregates were more abundant in forest soils owing to aggregate formation.

3.3 | Soil Water-Holding Capacity

Kaolinite application did not increase the water retention time for each soil sample site. However, the soil water content of the 6Y treated soils was higher than that of the control untreated soils (Figure 4). After 25 days of incubation, the 1% and 5% kaolinite treatments maintained higher water content than the untreated soil in 0Y soils, with a similar trend observed in the 1Y soils after 20 days of incubation. The 6Y soils treated with kaolinite showed an increased water-holding capacity, which was closer to that of the F soil samples from the reference site. A 15-day gap was observed in the soil water retention time between the treated and untreated early soils (0Y and 1Y soils) and the 6Y soil. These trends align with the higher vegetation cover in 6Y, which could have impacted the soil water content (Putra et al. 2024). The application of 1% kaolinite increased soil water retention in 6Y soils. However, the 5% kaolinite treatment showed results similar to those of the control treatment, particularly after 30 days of incubation.

The water retention curve (Figure 5) improved in both the 0Y and 1Y samples, particularly within the 337–1326 cm H_2O range. The 0Y soils treated with 1% and 5% kaolinite retained more water than the untreated soil, while the 1Y soils treated with 5% kaolinite showed the highest water retention. These results indicate that kaolinite application enhanced soil aggregation and water retention (Figure 5). Furthermore, the pore diameter of 2–10 μm, corresponding to the applied suction pressure, indicates the formation of silt-sized aggregates (< 53 μm).

The application of kaolinite to 6Y soils shifted the soil water retention curve, and the results were similar to those of the forest site. Although the overall water retention curve approaching that of forest sites was likely due to vegetation recovery, the increase in moisture content observed with kaolinite application is presumed to be due to the effect of kaolin itself. Even applying 1% kaolinite to the 6Y soils was sufficient to improve their water holding capacity, confirming its potential to enhance soil restoration as soil organic matter begins to establish.

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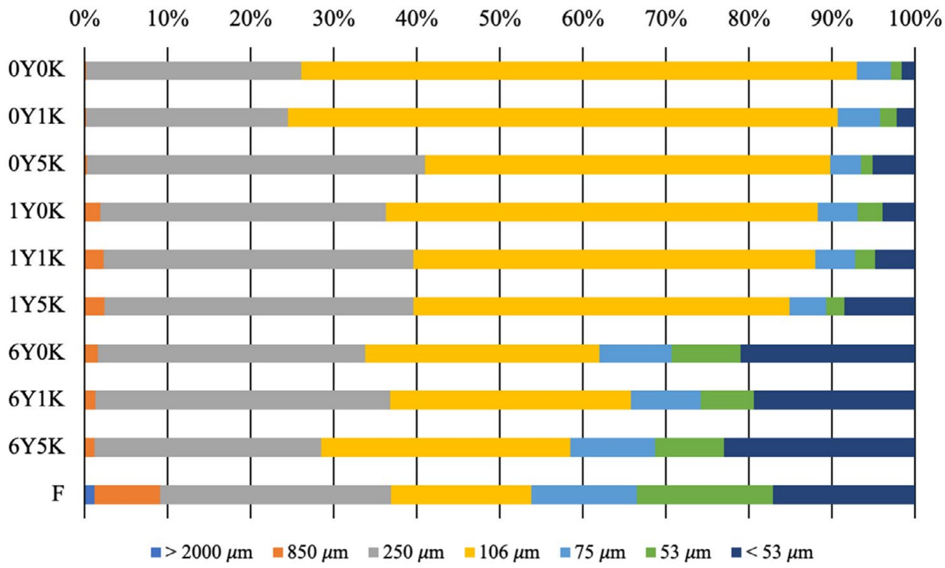

FIGURE 2 | Soil aggregate size distribution of Belitung post-tin-mined soils. Y, years since mining was stopped; K, percentage of kaolinite application; F, forest. [Colour figure can be viewed at wileyonlinelibrary.com]

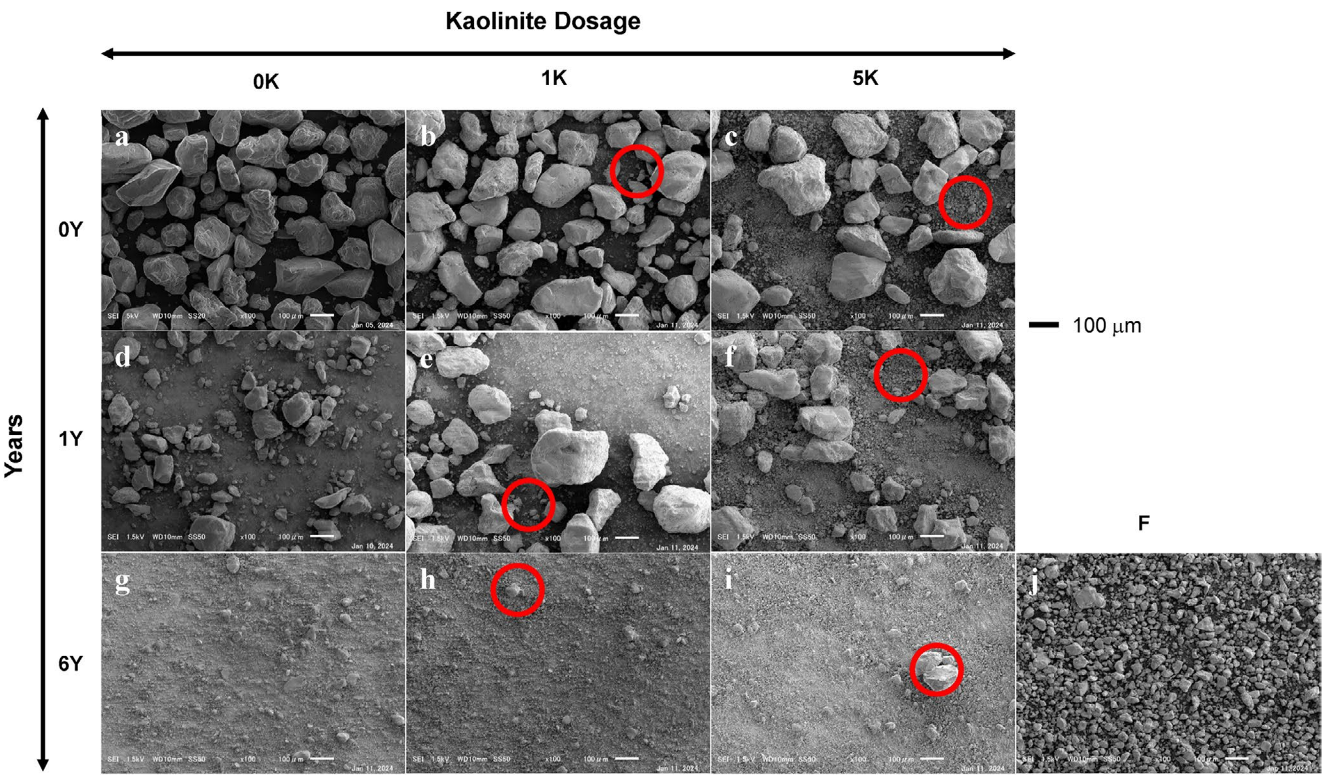

FIGURE 3 | SEM image of Belitung post-tin-mined soils. (a) 0Y0K, (b) 0Y1K, (c) 0Y5K, (d) 1Y0K, (e) 1Y1K, (f) 1Y5K, (g) 6Y0K, (h) 6Y1K, (i) 6Y5K, (j) F. The red circles show the silt-sized or micro aggregates in treated soils. Y, years since mining was stopped; K, percentage of kaolinite application; F, forest. [Colour figure can be viewed at wileyonlinelibrary.com]

3.4 | Soil Erodibility

As shown in Figure 6 and Table 2, forest soils exhibit a low erodibility index (*K*-factor), indicating that the natural environment can withstand environmental change. In contrast, the 0Y, 1Y, and 6Y soils without kaolinite exhibited extremely high erodibility indices, indicating degraded soil environments. However, the erodibility index of post-mined soil was significantly reduced by kaolinite application. The application of 1% kaolinite to mined soils was sufficient to enhance soil stability in 1Y soils. Further, the enhancement was much higher for the 5% kaolinite treatment compared to the 1% kaolinite treatment in 0Y soils. In addition, kaolinite application to early stage restoration soils (0Y and 1Y) effectively reduced the K-factor. Although vegetation had already established in the 6Y soils, kaolinite application significantly reduced soil erodibility compared with the control treatment.

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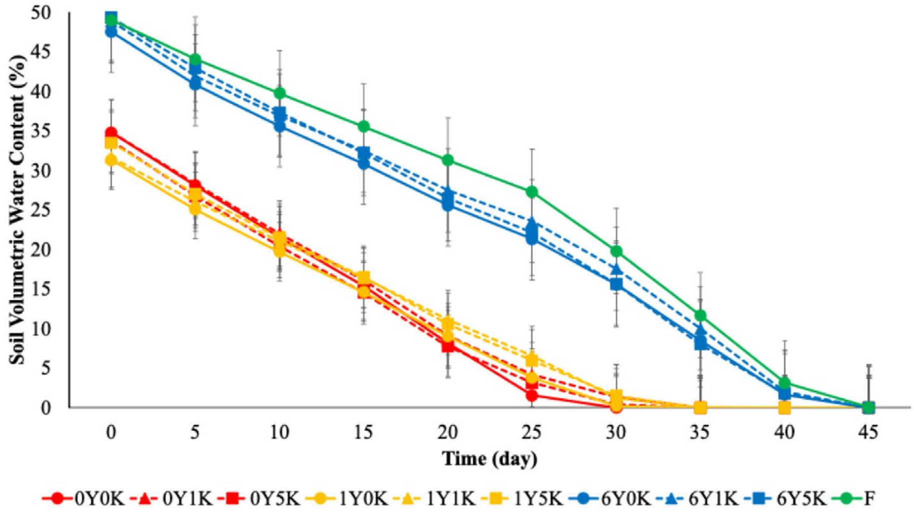

FIGURE 4 | Soil-water retention time of Belitung post-tin-mined soils. [Colour figure can be viewed at wileyonlinelibrary.com]

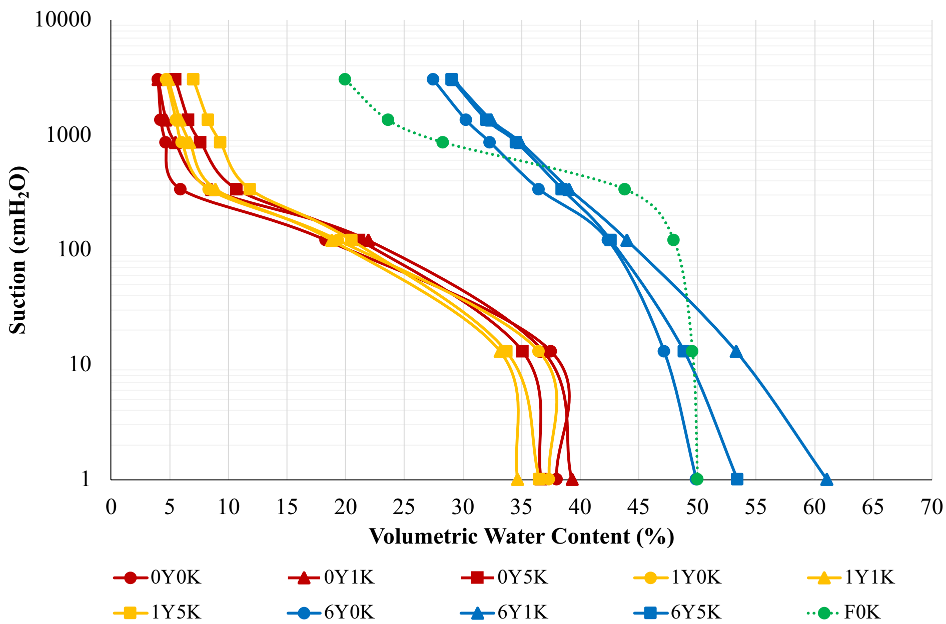

FIGURE 5 | Soil-water retention curve of Belitung post-tin-mined soils. [Colour figure can be viewed at wileyonlinelibrary.com]

3.5 | Principal Component Analysis

The results of the PCA are presented in Figure 7. Based on the observed trend, we can estimate that the horizontal axis, representing principal component 1, is related to the period after the completion of mining, and the vertical axis, representing principal component 2, is related to kaolinite application. We observed that the 5% kaolinite treatment had a different data cluster than that of the untreated soil. The PCA results confirmed that both untreated and treated soils contained different quantities of fine soil aggregates. Kaolinite-treated soils mostly contained soil aggregates of size 250 μm and 850 μm, particularly in the 0 and 1 year soil samples. This analysis indicated that kaolinite application effectively reduced soil erodibility during the early stages of soil restoration. The PCA arrow of soil erodibility (Ser) indicated that the mined soil without kaolinite would experience severe erosion. The PCA confirmed that an improvement in soil water retention time, water content at 1000 cm H_2O (growth-limiting water potential), and abundance of soil aggregates of 53 μm size were related to the post-mining period.

4 | Discussion

4.1 | Impact of Kaolinite Application on Soil Aggregates

Kaolinite application improved the abundance of silt-sized aggregates at all sites. An increase in the fraction of 250 μm in grain size was observed in the 0Y samples at 5% kaolinite treatment, the 1Y samples at 1% and 5% kaolinite treatments, and at 1% kaolinite treatment in the 6Y samples. In the 0Y, 1Y, and 6Y samples, an increase in soil silt-sized aggregates with a grain

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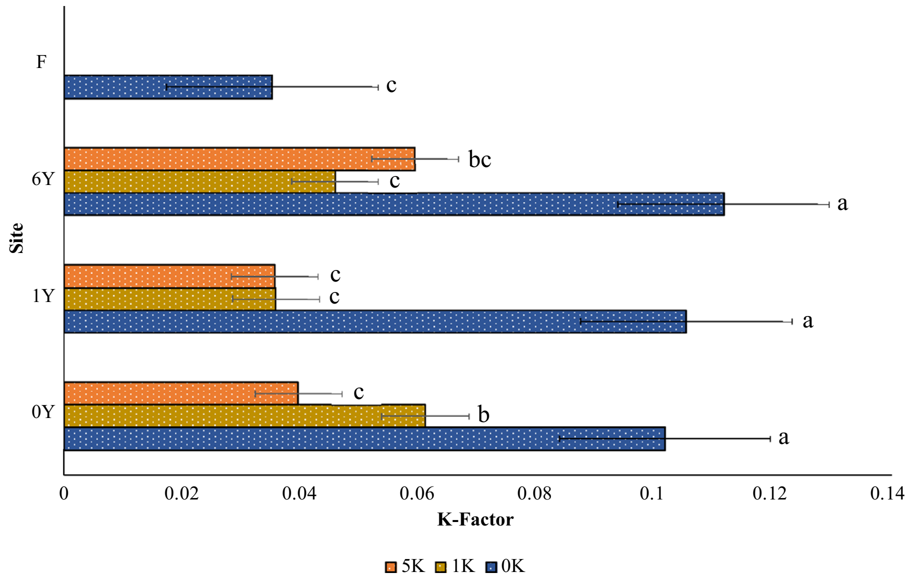

FIGURE 6 | Soil erodibility of Belitung post-tin-mined soils. Small letters indicate a significant difference between the treatments (Tukey's test α: 0.05). [Colour figure can be viewed at wileyonlinelibrary.com]

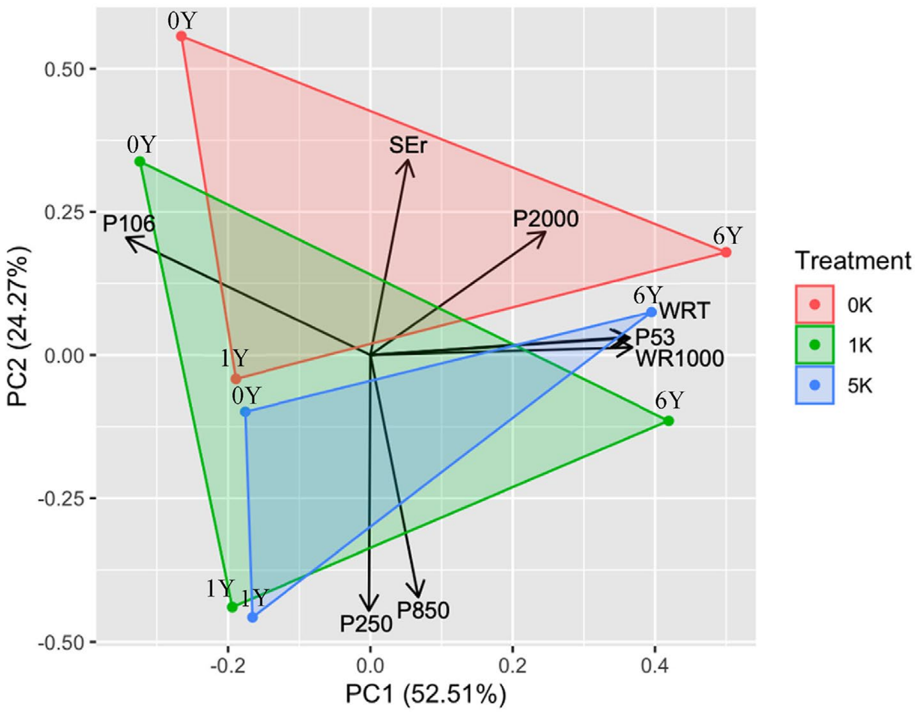

FIGURE 7 | Interaction between parameters of the experiment. P, particle sizes (53 μm, 106 μm, 250 μm, 850 μm, 2000 μm); WRT, water retention time; WR1000, water retention at 1000 cmH_2O; SEr, soil erodibility. The arrow directions show that the data distribution tends toward certain soil treatments. [Colour figure can be viewed at wileyonlinelibrary.com]

size < 53 μm was observed (Figure 2). However, whether the increase in the < 53 μm particles after the addition of kaolinite was caused by kaolinite promoting the aggregation process or from the kaolinite particles themselves was unclear; thus, we have employed SEM for further investigation.

Ye et al. (2019) reported that applying subsurface clay soil at a rate of approximately 25 $t\,ha^{-1}$ (equivalent to approximately 1% of the soil mass in the top 20 cm) increased the clay content but did not alter the overall soil texture class or silt fraction, indicating that the amendment amount was sufficient to modify the clay proportion without shifting the texture. However, the SEM image (Figure 3) showed increased soil aggregates of size < 53 μm in the post-mined soils due to kaolinite application. The clay particles themselves cannot be observed at this image resolution; therefore, we can assume that these soil particles are aggregates formed by the addition of clay, confirming that clay minerals are crucial for binding during the formation of soil aggregates (Totsche et al. 2018). Therefore, we can determine that the 53 μm-sized particles in Figure 2 contain many aggregates.

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TABLE 2 | The value of K-Factor's components.

Site	Kaolinite application	Soil texture (M)	Soil structure (*s*)	Water permeability (*p*)
0Y	0K	8839.67	3	1
	1K	5725.07	3	1
	5K	3891.39	3	1
1Y	0K	9115.00	3	1
	1K	3666.23	3	1
	5K	3652.73	3	1
6Y	0K	9210.33	3	3
	1K	4005.66	3	3
	5K	5129.28	3	3
F	0K	3513.09	2	4

The incorporation of kaolinite into sandy soils enhanced silt-sized and microaggregate development.

The SEM images revealed larger soil aggregates in the 6Y soils, which may be attributed to the binding effect of kaolinite, potentially supported by the activity of several groups of Proteobacteria present in the soil (Mitchell et al. 2016; Putra et al. 2024). Microbial activity associated with organic matter decomposition and wet–dry cycles strongly promotes soil aggregation (Rabbi et al. 2024). The fine sandy soils at 6Y had smaller particles than the bare sandy soil. Sand fractions in the 0Y and 1Y soils were captured the most because of soil washing processes during tin mining, which decreased the number of silt and clay particles (Nurtjahya et al. 2017). The soil particle size exhibited a trend of increasing coarseness with increasing soil desertification (Z. Liu et al. 2024).

In the particle size analysis of 6Y and F soils, particles of 2000 and 850 μm were detected to some extent, but were not visible in the SEM images. This discrepancy is likely due to the high proportion (nearly 20%) of silt and clay particles ($< 53\,\mu$m), which adhered to the adhesive tape during SEM preparation, whereas larger particles failed to stick and were lost, leading to the preferential imaging of finer fractions. Despite this limitation, the combined evidence from particle size analysis and SEM observations indicates that kaolinite application effectively promoted the formation of micro- or silt-sized aggregates. These findings support the study objective by demonstrating that kaolinite plays a crucial role in improving soil aggregation in post-mined sandy soils, thereby contributing to soil structural recovery.

4.2 | Impact of Kaolinite Application on Soil Water-Holding Capacity

The soil moisture characteristic curve shown in Figure 5 reveals a significant increase between 337 and 1326 cm H_2O. According to capillary theory (Hillel 1998), this corresponds to a pore size between 8.9 and 2.3 μm. Based on the packing geometry (Marshall et al. 1996), this indicates an increase in particles of approximately 3–10 times this size, ranging from 6.9 to 26.7 or 23 to 89 μm. This represents an increase in aggregates within the range referred to as silt-sized aggregates ($< 53\,\mu$m). The formation of silt-sized aggregates of approximately 50 μm in diameter is important for improving water retention (Totsche et al. 2018) and indicates that the initial stage of aggregate formation has occurred.

Similarly, in the 6Y sample, the application of kaolinite improved the water-holding capacity at 337 and 1326 cm H_2O, which correspond to silt-sized aggregates (Figure 5). However, the water-holding capacity significantly increased near the saturated water content, which corresponds to micro- and macro-aggregates. This may be attributed to the soil containing approximately 0.2% organic matter (Figure 5).

Kaolinite maintained higher water retention in post-tin-mined soils for 25 days in the early age soils (0 and 1 year) and 25–35 days in the soil with organic matter content (6 year) than in the control (0K) soils. Clay is a natural absorbent with a large surface area. Kaolinite applied to 6Y soils showed higher soil water retention, indicating that the combination of clay and organic matter at the site could further improve the water-holding capacity of sandy soils (Figure 5). Similarly, in another study, clay treatment greatly enhanced water retention and availability for plants in the top 40 cm of soil (Mi et al. 2020).

The volumetric water content in the 6Y soils at 200 cm H_2O to 800 cm H_2O was $> 32\%$ (Figure 5) and had values similar to those of the woody soil cover (Ming et al. 2024). Although the 6Y site had established vegetation where water repellence could develop, this effect may have been mitigated by the large surface area of kaolinite (Daniel et al. 2019; Diamantis et al. 2017; Yu et al. 2022). These findings suggest that kaolinite application is a promising strategy for improving soil structure and hydrological function in degraded sandy soils, thereby supporting vegetation establishment and long-term land rehabilitation.

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4.3 | Impact of Kaolinite Application on Soil Aggregate Stability

Although efforts to restore degraded soils have often focused on adding organic matter, in this study, the external addition of kaolinite made a considerable difference. The application of 1% kaolinite influenced soil aggregation because the clay minerals promoted particle adhesion, contributing to the formation of 2–10 μm silt-scale aggregates and 250–840 μm aggregates, even without organic matter. Furthermore, in tropical climates, where organic matter is rapidly decomposed owing to high temperatures and moisture levels, the addition of clay, which remains stable under such conditions, offers a more durable option for improving soil properties.

Kaolinite application to tin-mined soils produces more stable small soil aggregates. Pi et al. (2020) studied the impact of clay amendments on the geometric mean diameter of aggregates and suggested that they could effectively stabilize erosive sandy soil ecosystems. Kaolinite has been abundant in Belitung Island (Estiaty and dan Fatimah 2014). Therefore, it can be used as a stabilizer for sandy soils at the beginning of soil rehabilitation. The clay fraction and soil organic carbon are essential for controlling microporosity and soil hydraulic conductivity (Koop et al. 2023). Organic matter is relatively more stable in the presence of clay than when it is present alone (Yang et al. 2022).

Enriching kaolinite with organic matter can further improve plant growth (Al-Swadi et al. 2024). Variations in soil particle size influence carbon and nitrogen dynamics by facilitating the dispersion of organic matter (Amorim et al. 2023). Adding clay to sandy soils enhances carbon sequestration by reducing carbon dioxide emissions (Shi and Marschner 2013). Additionally, kaolinite clay can aid in environmental decontamination because of its high adsorption capacity (Chen et al. 2023; Shang et al. 2024). In the current study, kaolinite incorporation into tin-mined soils improved soil aggregate stability and provided a more favorable environment for organic matter retention. The stabilization of small aggregates reduces the risk of rapid organic matter loss under tropical conditions, indicating that kaolinite can play a dual role in both structural improvement and carbon conservation. These findings highlight the potential of locally available kaolinite as a sustainable amendment for rehabilitating degraded sandy soils.

4.4 | Interactions Between Soil Properties

The PCA results showed that the 0% and 5% kaolinite treatments were separated into different groups, indicating a significant difference. In contrast, the 1% treatment overlapped with both groups and was not significantly different from either. This finding suggests that even a 1% kaolinite addition may be sufficient to enhance soil aggregate stability under the conditions examined in this study.

The soil aggregate size distribution showed that the number of particles in the 250 μm category increased with kaolinite application. Moreover, soil erodibility was highest at 0% kaolinite and reached values similar to those of forest soil treated with 1% and 5% kaolinite. The PCA results were representative of the environmental characteristics of these soils.

The PCA results confirmed that kaolinite-amended soils exhibited lower soil erodibility than control (untreated) soils because kaolinite-amended soils contained relatively more fine soil aggregates. The treated soil exhibited a higher water-holding capacity, especially under drier conditions. Although 1% kaolinite was sufficient to improve water retention, the rate had to be increased to 5% to achieve relatively stable soil aggregates. Cardoso et al. (2023) reported that a kaolinite percentage between 5% and 10% is optimal for enhancing bio-cementation in soil. Another study showed that applying clay to sandy soils during a single wet–dry cycle enhanced soil aggregation (Wagner et al. 2007). Although the application of organic matter is a common practice for the restoration of degraded soils, the application of clay particles has promising results showing enhanced formation of soil aggregates and water-holding capacity, reduced soil erodibility, and demonstrating the suitability for tropical soil restoration where rainfall is intense. These findings will be crucial for addressing the higher soil erosion in the initial land reclamation stages on Belitung Island. Organic matter is lightweight, washes away during heavy rain, and decomposes under strong sunlight. Therefore, the difficulties in using organic matter amendments in the first stage of soil restoration can be resolved by adding clay particles. As kaolinite is abundant on Belitung Island and easy to find in the surrounding post-tin mining area, the cost of utilizing this clay as a soil restoration agent will not be prohibitive.

Owing to the limited amount of soil that could be imported, this study cannot fully guarantee the long-term reproducibility of the findings or ensure the consistency of samples collected at an island-wide scale. However, consistent trends still emerged under these conditions, strengthening the reliability of our findings and highlighting the robustness of the observed effects of kaolinite application. Our results should be confirmed by long-term field experiments, which we intend to perform in the future.

5 | Conclusions

This study demonstrates the potential of kaolinite as an effective amendment to improve the physical properties of degraded, post-tin-mined sandy soils in tropical environments. The final conclusions can be summarized in the following four main points:

1. Kaolinite application enhances soil aggregate formation in post-mined sandy soils, particularly improving silt-sized and small macroaggregate abundance (< 53 μm and 250–850 μm), which is critical for early stage soil structure development and long-term soil stability.
2. The soil water-holding capacity was improved, especially at 337–1326 cm H_2O in the early stage (0Y and 1Y) and for mid-stage (6Y) reclaimed soils, 1% kaolinite was sufficient to achieve water retention levels comparable to natural forest soils (F), thus aiding re-vegetation and microbial activity.

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3. Soil erodibility (K-factor) was effectively reduced with kaolinite across all post-mined sites, with a greater impact at earlier succession stages. This demonstrates its potential as a reliable soil stabilizer in tropical environments, where organic matter alone may be insufficient because of rapid decomposition.
4. The PCA results indicated a clear separation between the control and kaolinite-treated soils along the axes associated with post-mining recovery time and treatment level. Variables related to water retention, fine aggregate abundance, and reduced erodibility were strongly associated with kaolinite application, confirming its positive influence on soil restoration metrics.

Kaolinite is a viable and sustainable amendment for soil rehabilitation in tropical, post-tin-mined landscapes due to its resistance to weathering, natural abundance in the region, and compatibility with developing vegetation and microbial communities, making it an effective alternative or complement to organic matter in restoration efforts. Long-term monitoring at actual field sites will be essential in future studies to assess the full extent of the recovery.

Author Contributions

Conceptualization: Yasushi Mori and Hirmas F. Putra. Methodology: Hirmas F. Putra and Yasushi Mori. Formal analysis and investigation: Hirmas F. Putra and Yasushi Mori. Writing – original draft preparation: Hirmas F. Putra. Writing – review and editing: Yasushi Mori. Funding acquisition, Resources, and Supervision: Yasushi Mori.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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