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Recovery of soil carbon pools and C–N stoichiometry under drought in degraded tin-mined soils using organic, inorganic, and bio-amendments

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Abstract. *Rahayu, Erdaswin F, Rosariastuti R, Dewi WS, Fatimah, Herawati A, Ichsan N. 2025. Recovery of soil carbon pools and C–N stoichiometry under drought in degraded tin-mined soils using organic, inorganic, and bio-amendments. Asian J Agric 9: 818-830.* Large-scale tin mining on Bangka Island, Indonesia, has severely degraded soils, resulting in low carbon reserves and imbalanced C–N stoichiometry, particularly under seasonal drought. This study evaluated the effectiveness of an integrated amendment strategy to restore soil carbon pools and improve C–N stoichiometry under these challenging conditions. A 100-day screenhouse experiment was conducted on degraded tin-mined soil using a Completely Randomized Design. Treatments included municipal compost, dolomite, Lactic Acid Bacteria (LAB), and NPK fertilizer, applied individually and in combination. Key physicochemical properties, carbon pools, stoichiometric ratios, and their interrelationships were analyzed using ANOVA, Redundancy Analysis, and Pearson correlation. The integrated combination treatment was synergistically superior (ANOVA, $p<0.01$). The recovery of carbon pools was marked by a seven-fold surge in microbial biomass carbon to 703.73 mg kg^{-1} and a near-doubling of the soil organic carbon stock to 29.21 Mg C ha^{-1}. The improvement in C–N stoichiometry was evidenced by the optimization of key microbial efficiency ratios, with the MBC/SOC ratio reaching 13.99% and the MBC/TN ratio increasing to 45.18%. Redundancy Analysis confirmed that compost-based treatments formed a distinct, functionally efficient group. Furthermore, Pearson correlation revealed the integrated nature of this recovery, showing a tight coupling between the accumulation of key carbon pools (SOC and MBC; $r=0.909$) and the enhancement of microbial C-use efficiency. In contrast, the dolomite amendment created a dysfunctional system by causing a massive accumulation of Dissolved Organic Carbon (DOC) to 279.18 mg kg^{-1} without a corresponding increase in microbial biomass. A holistic, multi-ameliorant strategy anchored by a substantial organic matter base is essential for restoring ecosystem functions. This approach provides a robust and practical framework for the sustainable land management of degraded post-tin mining landscapes, offering a viable pathway to rebuild soil health and enhance drought resilience.

Keywords: Drought stress mitigation, microbial efficiency, multi-ameliorant, post-tin mining soils, soil organic carbon stocks

INTRODUCTION

Large-scale tin mining on Bangka Island, Indonesia, has led to severe soil degradation. Mining areas expanded from 144,783.81 ha in 2018 to 156,531.3 ha in 2021, covering almost 28% of the province (Government of the Province of Bangka Belitung Islands 2022). Open-pit mining removes the topsoil and leaves sandy substrates dominated by quartz, resulting in a sharp decline in Soil Organic Carbon (SOC) pools, structural damage, high acidity, and reduced microbial activity, which together compromise soil fertility and ecosystem function (Oktavia et al. 2015; Sukarman et al. 2020).

This degradation is exacerbated by the island's tropical climate, which is prone to seasonal droughts. In dry years such as 2014, 2015, 2019, and 2023, monthly rainfall dropped to 0-39 mm (BMKG 2024). The sandy texture of tin-mined soils provides poor water retention, making them highly susceptible to percolation and evaporation (Erdaswin et al. 2025). Drought strongly suppresses microbial activity when soil moisture falls below 60%, disrupting carbon and nutrient cycling and accelerating ecosystem decline (Borowik and Wyszkowska 2016; Chowdhury et al. 2019; Bian et al. 2022; Tian et al. 2024). Drought can also disrupt the interaction between carbon and nitrogen cycles in the soil, thereby weakening mineralization and nitrification processes (Li et al. 2020). Deng et al. (2021) confirmed this by stating that drought decreases soil organic carbon by 3.3% due to reduced litter input and decomposition (-8.7% and -13.0%, respectively), while simultaneously increasing mineral N (+31%) but suppressing N mineralization (-5.7%) and nitrification (-13.8%).

Given the escalating degradation, immediate restoration of soil functions is essential, particularly on post–tin mining lands prone to prolonged drought. Land reclamation through amendment applications is a key strategy (Larney and Angers 2012). A range of organic, inorganic, and biological amendments can be applied (Clemente et al. 2019; Sinduja et al. 2023). Organic matter, such as municipal waste compost, replenishes carbon stocks and improves aggregation and water retention (Omokaro et al. 2024; Song et al. 2025). Inorganic amendments like dolomite can reduce acidity (Pratiwi et al. 2020) and supply calcium (Ca) and magnesium (Mg) to enhance nutrient availability, aggregation, and structural stability (Sae-Tun et al. 2025). Biological amendments, including Lactic Acid Bacteria (LAB) serum, can accelerate organic matter decomposition (Consabo et al. 2023). LAB also increases microbial activity by enriching beneficial communities and modifying nutrient availability through enzyme and metabolite production, thereby improving soil biological quality (Panetto et al. 2023). Complementing these amendments with NPK fertilizer is equally important, as it replenishes macronutrients lost during mining (Barba et al. 2023), enhances SOC accumulation, and improves soil fertility and quality (Liu et al. 2017). Although these benefits are well established under normal conditions, integrated applications of organic, inorganic, and biological amendments show synergistic effects on degraded soils (Creamer et al. 2024), yet their performance under drought stress remains poorly understood. To evaluate the success of these strategies, indicators that capture soil biological and biogeochemical responses are needed, including carbon–nitrogen stoichiometry.

Restoring carbon pools and achieving a balanced C–N stoichiometry (C/N, MBC/SOC, MBC/TN, DOC/SOC, DOC/TN) is essential because these ratios indicate microbial efficiency and soil functional recovery (Sun et al. 2020a; Zhang et al. 2023). Ratios such as C/N and MBC/SOC offer a clearer picture of ecosystem function than SOC alone, as they reflect microbial nutrient use efficiency and reveal nutrient limitations that influence soil carbon and nitrogen cycling (Li et al. 2019). Moreover, C–N stoichiometry in soil, plants, and microbes provides critical information for assessing the responses of above-ground and below-ground systems to broader environmental changes (Moe et al. 2005). Imbalances in these ratios can signal substrate limitations or the accumulation of labile compounds that suppress microbial activity; therefore, effective recovery requires simultaneous improvement across these stoichiometric indicators (Dongdong et al. 2023; Woś et al. 2023).

Currently, there is a knowledge gap regarding the performance of an integrated multi-ameliorant strategy in restoring carbon pools and stoichiometric balance under severe drought stress. We hypothesize that combining compost, dolomite, LAB, and NPK will synergistically increase SOC stocks, stimulate microbial biomass, and restore C–N balance even under water-limited conditions. This study aims to evaluate this integrated approach, providing novel, climate-adaptive insights for reclaiming severely degraded tropical tin-mined lands.

MATERIALS AND METHODS

Study area

The experiment was conducted in a screenhouse at the Faculty of Agriculture, Universitas Sebelas Maret, Karanganyar, Central Java, Indonesia (7°37′47.58″ S, 110°56′52.06″ E; 170 masl) from November 2024 to February 2025. The soil used as the growing medium was collected from a recently mined tin area in Koba Sub-district, Central Bangka District, Bangka Island, Indonesia (2°30′02.58″ S, 106°23′35.78″ E; 4 masl) (Figure 1). This site represents severely degraded post-tin-mined soil, dominated by sandy textures with minimal organic matter due to complete topsoil removal during open-pit mining.

Procedures

Soil amendments

Municipal Compost (MC) was produced using a modified bucket composting method with 12 ventilation and drainage holes. Raw materials from the Putri Cempo landfill (Surakarta, Indonesia) were shredded, moistened to optimal levels, and mixed with 100 mL of 1% bio-activator solution, 30 mL of molasses, and a small amount of inorganic fertilizer (12 g urea, 8 g SP-36, and 4 g KCl per 5 kg of material). The compost was incubated for 60 days with periodic aeration until fully mature. Its chemical properties are summarized in Table 1.

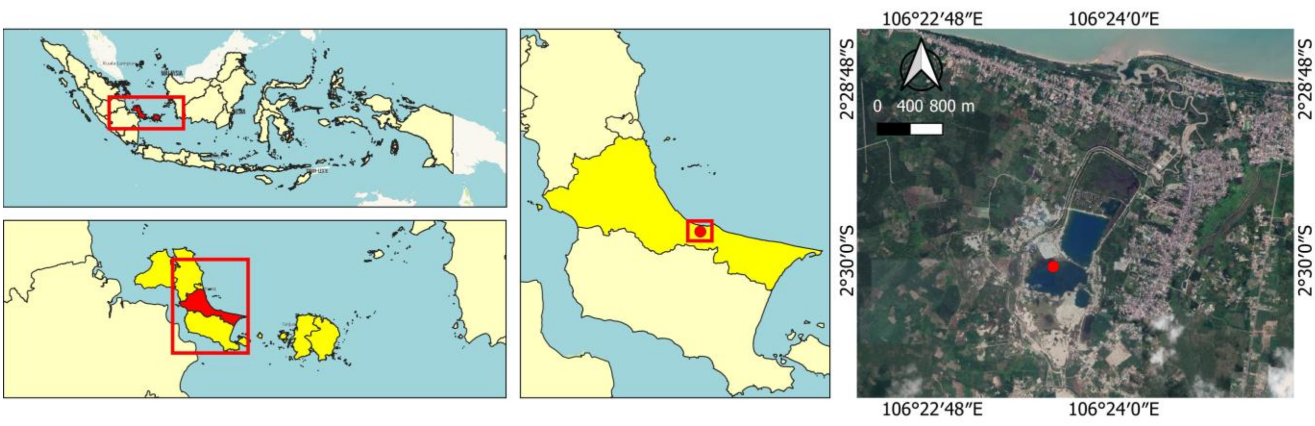

Figure 1. The location of the tin mined soil media collection on Bangka Island, Indonesia, is to be used as an experiment

Lactic Acid Bacteria (LAB) serum was prepared by fermenting rice wash water for three days to cultivate indigenous LAB. The ferment was then mixed with fresh milk at a 1:10 ratio and re-fermented for 3-5 days until the serum separated from the curdled protein. The serum was filtered and diluted 1:500 with chlorine-free water before application. Dolomite ($CaMg(CO_3)_2$) and NPK fertilizer (16:16:16) were applied according to the experimental design.

Drought simulation

The experiment was conducted for 100 days without irrigation to simulate the severe drought conditions typical of Bangka Island's dry season. Historical rainfall data (2013-2023) indicate that months with rainfall below 150 mm are classified as dry (Xie et al. 2011; Safril 2020), with extreme events as low as 0-39 mm month^{-1} recorded in 2014, 2015, and 2023. This zero-irrigation approach reproduces the lowest rainfall conditions observed in the region and enables the evaluation of amendment performance under critical water-limited conditions. Historical monthly rainfall patterns are shown in Figure 2.

Experimental design and layout

The experiment followed a Completely Randomized Design (CRD) with five replications per treatment (25 total experimental units). Each unit consisted of a 19.5 cm diameter pot filled with 4 kg of homogenized, air-dried, and sieved (2 mm) post-tin mining soil, with pots spaced 30 cm apart (Figure 3). The five treatments were: (i) NPK fertilizer only; (ii) Municipal Compost (MC) + NPK; (iii) Lactic Acid Bacteria (LAB) + NPK; (iv) Dolomite + NPK; and (v) a full Combination of all amendments. Application rates were calculated on a field-equivalent basis. Solid amendments were mixed into the soil one week before incubation: NPK (16:16:16) at 305 kg ha^{-1} (0.42 g pot^{-1}), based on recommendations from the (UGA 2015); MC at 60 t ha^{-1} (92 g pot^{-1}); and dolomite at 10 t ha^{-1} (13.9 g pot^{-1}). Liquid LAB serum was applied on day one of incubation at 16 L ha^{-1} (13 mL pot^{-1}).

Data collection

Experimental design and layout

Soil samples were analyzed before and after the 100-day experiment to evaluate changes in physical, chemical, and biological properties. The observed soil physical parameters included Soil Moisture (SM), measured using the gravimetric method, and Bulk Density (BD), using a similar method, both referencing the guidelines from Balittanah (2022). The analyzed soil chemical properties included Soil Organic Carbon (SOC) using the Walkley and Black method (Nelson and Sommers 1982), and Soil Organic Carbon Stock (SOCS), calculated based on the equation: SOC (%) × BD × soil depth (cm) × 10, as used by Zeng et al. (2021). Additionally, Dissolved Organic Carbon (DOC) was determined through K_2SO_4 extraction (Yang et al. 2012), and Total Nitrogen (TN) content was analyzed using the Kjeldahl method (Rhee 2001). The soil biological parameter, namely Microbial Biomass Carbon (MBC), was analyzed using the fumigation-extraction method according to the procedure of Vance et al. (1987). From these parameters, soil microbial stoichiometry and efficiency indicators were also calculated, such as the C/N, MBC/SOC, MBC/TN, DOC/SOC, and DOC/TN ratios.

Table 1. Chemical characteristics of the municipal solid waste compost used in the experiment

Parameters	Value
pH	7.11
Electrical conductivity (dS/m)	0.122
Organic carbon (%)	24.06
Total N (%)	1.24
Total P (%)	0.17
Total K (%)	4.61
C/N	19.40
Available P (ppm)	5.70
Available K (meq/100 g)	30.95

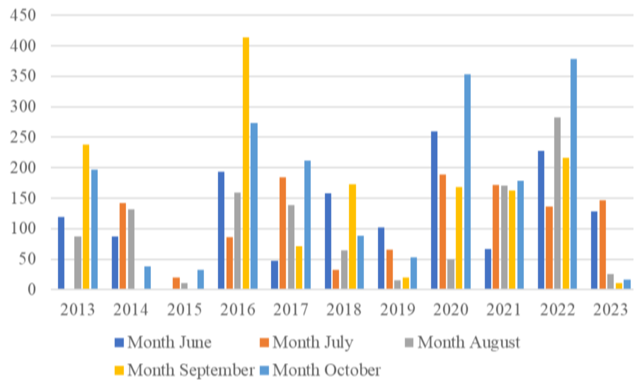

Figure 2. Historical monthly rainfall (June-October) in Bangka Island, Indonesia, from 2013 to 2023 (BMKG 2024)

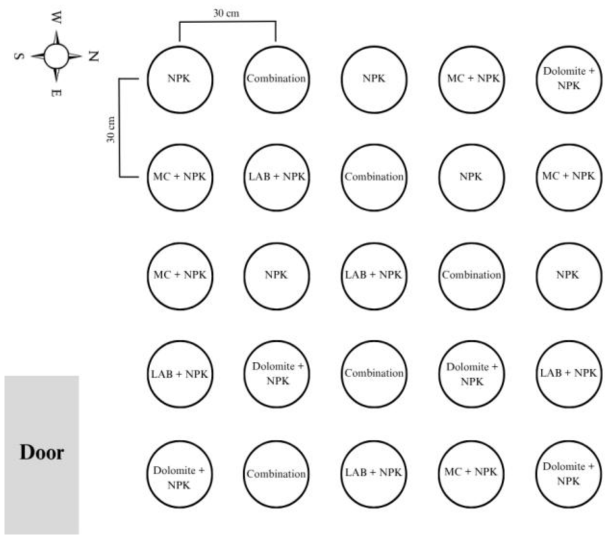

Figure 3. Layout of the pot experiment in the screenhouse using a Completely Randomized Design (CRD) with five treatments and five replications

Data analysis

Before analysis, all data were tested for normality using the Shapiro-Wilk test and for homogeneity of variances with Levene's test. All data were analyzed using Analysis of Variance (ANOVA) at a 5% significance level, and treatment means were separated with Duncan's post-hoc test. Redundancy analysis (RDA) in RStudio was used to assess clustering patterns and the relationships between soil properties and treatments. In contrast, Pearson correlation analysis was conducted to examine relationships among post-treatment soil properties. All statistical analyses were performed using IBM SPSS version 27 and RStudio software.

RESULTS AND DISCUSSION

Response of soil physical, chemical, and biological properties to organic-mineral amendments in degraded tin-mined soils under simulated drought

The application of organic-mineral amendments showed a highly significant overall effect on the physical, chemical, and biological properties of the degraded tin-mined soil (ANOVA, $p<0.01$; Table 2). Regarding physical properties, the amendments significantly reduced soil compaction. The MC+NPK (1.23 g cm^{-3}) and Combination (1.28 g cm^{-3}) treatments produced a significantly lower Bulk Density (BD) compared to the Initial Soil (1.39 g cm^{-3}) (Duncan test, $p<0.05$). Despite the drought, the Combination treatment also maintained the highest soil moisture (0.56%), which was more than double that of the treatments without organic matter (0.22-0.24%). Chemically, the compost-based treatments substantially increased carbon pools. The Combination and MC+NPK treatments yielded the highest Soil Organic Carbon (SOC) concentration (0.51%) and stock (SOCS; up to 29.21 Mg C ha^{-1}), which was nearly double the SOCS of the Initial Soil (15.05 Mg C ha^{-1}). A key contrasting finding was observed in the Dolomite+NPK treatment, which produced a significantly higher Dissolved Organic Carbon (DOC) concentration (279.18 mg kg^{-1}) than all other treatments. Total Nitrogen (TN) was highest in the compost- and LAB-amended treatments (0.16%). Biologically, the soil's Microbial Biomass Carbon (MBC) responded sharply to organic matter. The Combination treatment produced the highest MBC (703.73 mg kg^{-1}), which was over seven times greater than the Initial Soil (99.12 mg kg^{-1}) and thirteen times greater than the NPK-only treatment (53.26 mg kg^{-1}), indicating a massive stimulation of microbial life.

These findings not only validate our initial hypothesis but also point to the immense potential of an integrated, multi-ameliorant treatment in significantly enhancing carbon pools, stoichiometry, and overall soil health, even in the most challenging drought conditions. The exceptional performance of the Combination treatment serves as a powerful example of the potential of synergistic effects. The improvement in physical properties is a crucial step in the journey towards recovery. The decrease in bulk density, primarily due to the dilution effect of low-density compost and the creation of new pore space, has been shown to lower BD below root-growth-inhibiting thresholds, paving the way for a promising future in soil treatment (McGrath and Henry 2016; Reynolds et al. 2020). This enhanced porosity, in turn, directly improves water storage capacity. The mechanisms were multifaceted: compost acted as a sponge, while dolomite likely promoted flocculation, and LAB-produced exopolysaccharides (EPS) acted as binding agents, creating more stable soil aggregates (Adessi et al. 2018; Jurášková et al. 2022; Zhan et al. 2022).

The recovery of the soil's biogeochemical engine is evident from the carbon and nitrogen dynamics. The doubling of the SOC stock in compost-based treatments confirms that organic amendments are non-negotiable for rebuilding carbon reserves. More importantly, the massive surge in MBC signifies a successful reactivation of the soil's biological functions (Blagodatsky et al. 2010), a process known to be inhibited by low soil moisture (Bian et al. 2022). Compared to the study by Qu et al. (2023), which stated that drought reduced MBC by up to -22.7%, MBC in this study increased even under drought conditions, especially with the addition of carbon substrate. This may occur because microorganisms mobilize carbon reserves to produce protective metabolites such as amino acids (AA) and exopolymeric substances (EPS) to adapt to drought stress (Kakumanu et al. 2019).

The most intriguing finding was the dolomite dysfunction, where a spike in labile carbon (DOC) did not translate to microbial growth. This decoupling is likely due to a pH-induced increase in the solubility of organic compounds (Wu et al. 2021), but under drought, this newly available DOC could not be utilized by the water-stressed microbial community. This aligns with other studies in post-mining contexts where a multi-faceted approach proves superior (Creamer et al. 2024). The nitrogen dynamics also revealed important interactions. The modest increase in TN in compost-based treatments, despite the large organic input, can be attributed to the compost's C/N ratio, which may have led to initial microbial N immobilization, and the decrease in TN in treatments without an organic buffer highlights the risk of N loss via volatilization under drought (Crohn 2016; Ullah et al. 2020). Interestingly, the ability of the LAB+NPK treatment to increase TN without an organic C source is consistent with recent findings that LAB can promote nitrogen mineralization processes even in dry soil conditions (Murindangabo et al. 2023).

The successful restoration of these interconnected properties has significant long-term effects. By rebuilding a functional soil ecosystem, this integrated approach can lead to self-sustaining nutrient cycles. For larger-scale efforts, this strategy suggests that regional land reclamation policies for the vast post-tin mining areas on Bangka Island should prioritize the use of locally sourced organic materials as the cornerstone of any rehabilitation effort.

Improvement of soil carbon and nitrogen stoichiometry as indicators of functional recovery under drought conditions

The application of amendments had a highly significant effect on all measured C–N stoichiometric ratios ($p<0.01$;

Figure 4). The C/N ratio of the Initial Soil was very narrow (1.82). The compost-based treatments (MC+NPK and Combination) significantly widened this ratio to 3.29 and 3.26, respectively. Microbial C-use efficiency, measured by the MBC/SOC ratio, was highest in the Combination treatment (13.99%). Similarly, N-use efficiency, indicated by the MBC/TN ratio, surged in the compost treatments, reaching a peak of 45.18% in the Combination treatment, a statistically significant increase compared to all non-compost treatments. A key indicator of system dysfunction was observed in the DOC-related ratios. The Dolomite+NPK treatment produced an exceptionally high DOC/SOC ratio of 1.27 and a DOC/TN ratio of 2.14, both values being significantly higher than in any other treatment.

The significant shifts in C–N stoichiometry provide strong support for our hypothesis that the integrated amendment strategy could improve the soil's functional balance, a key indicator in evaluating the recovery of soil ecosystem function (Breza and Grandy 2025). The widening of the C/N ratio in compost-amended soils is a critical initial step in the recovery process. It signifies the input of a large carbon pool, which stimulates microbial activity and opens up the possibility for microbial nitrogen immobilization as a key process that helps retain nitrogen in the system, although the ratio remains below the ideal range often cited for soils, which is 8-12 (Shrestha and Lal 2007). The initially low C/N ratio (1.82) was a clear sign of an accessible carbon deficit (Qu et al. 2017), a condition that was reversed by compost addition but exacerbated in treatments without an organic C source (Li et al. 2022).

The dramatic increase in the MBC/SOC and MBC/TN ratios in the Combination treatment is the most direct evidence of a reactivated and efficient microbial community. The increase in the MBC/SOC ratio in the Combination treatment was 239.56% higher than in the Initial Soil. These results indicate that the combination of organic, inorganic, and microbial materials synergistically increases the proportion of microbial carbon relative to total soil organic carbon. This finding aligns with Wu et al. (2023), who reported that the combination of organic and inorganic treatments increased the MBC/SOC ratio by 47.95-193.18% compared to the control in soil. A higher MBC/SOC ratio indicates that a larger fraction of the soil's total carbon is in the form of living microbial biomass, a hallmark of an active and healthy soil ecosystem (Qu et al. 2017; Melendez et al. 2020). The exceptionally high MBC/TN ratio (45.18%) further demonstrates that microbes were efficiently converting available nitrogen into their biomass, a crucial function for building a self-sustaining nutrient cycle in degraded soils (Li et al. 2009).

In stark contrast, the Dolomite+NPK treatment exemplifies a "stoichiometrically decoupled" or dysfunctional system. The extremely high DOC/SOC and DOC/TN ratios reveal that while the amendment successfully increased the pool of labile, Dissolved Organic Carbon (DOC), this resource was not utilized by the microbial community. This aligns with studies that report severe nutrient limitations (in this case, nitrogen relative to carbon) can inhibit microbial processing of available substrates (Ren et al. 2020). The low DOC/SOC ratio in the compost treatments suggests that labile carbon was being efficiently consumed and integrated into more stable pools (Wang et al. 2021; Aumtong et al. 2023). The high pH induced by dolomite likely exacerbated the dysfunction by mobilizing DOC that the nitrogen-limited microbes could not assimilate, a phenomenon also observed in other post-mining contexts (Sae-Tun et al. 2025).

This detailed stoichiometric analysis underscores a key implication for restoration: simply increasing a single resource pool (like DOC) is insufficient for functional recovery. A successful strategy must provide a balanced suite of resources that enhances the overall efficiency of the microbial community, which was only achieved through a synergistic, multi-ameliorant approach.

Table 2. Soil physical, chemical, and biological parameters under organic-mineral amendments in simulated drought conditions

Treatment	Total Soil Parameters						
	BD	SM	SOC	SOCS	DOC	MBC	TN
	(g/cm³)	(%)	(%)	(Mg C/ha)	(mg/kg^{-1})	(mg/kg^{-1})	(%)
Initial Soil	1.39±0.05b	5.24±0.47a	0.24±0.02b	15.05±0.67b	9.73±1.44c	99.12±5.68c	0.14±0.03ab
NPK	1.34±0.03b	0.24±0.05c	0.24±0.01b	14.68±0.69b	15.41±4.38c	53.26±11.21d	0.11±0.03b
MC + NPK	1.23±0.03a	0.40±0.08bc	0.51±0.09a	28.04±4.75a	101.25±38.51b	471.65±43.36b	0.16±0.02a
LAB + NPK	1.34±0.03b	0.22±0.04c	0.23±0.03b	13.62±1.83b	85.98±14.74b	83.71±16.63cd	0.16±0.02a
Dolomite + NPK	1.33±0.05b	0.22±0.06c	0.22±0.03b	13.40±1.56b	279.18±31.02a	77.80±11.61cd	0.13±0.02ab
Combination	1.28±0.05a	0.56±0.06b	0.51±0.05a	29.21±3.74a	85.46±20.88b	703.73±57.55a	0.16±0.01a
Sig	**	**	**	**	**	**	*

Note: BD: Bulk Density, SM: Soil Moisture, SOC: Soil Organic Carbon, SOCS: Soil Organic Carbon Stock, DOC: Dissolve Organic Carbon, MBC: Microbial Biomass Carbon, TN: Total Nitrogen, ±: Standard deviation, Letter symbol: Numbers in the same column followed by different letters indicate significantly different according to Duncan test at the 5% level, while numbers in the same column followed by the same letter indicate not significantly different according to Tukey's test at the 5% level, and *: Very significant at p<0.05 (one-way ANOVA), **: Significant at p<0.01 (one-way ANOVA)

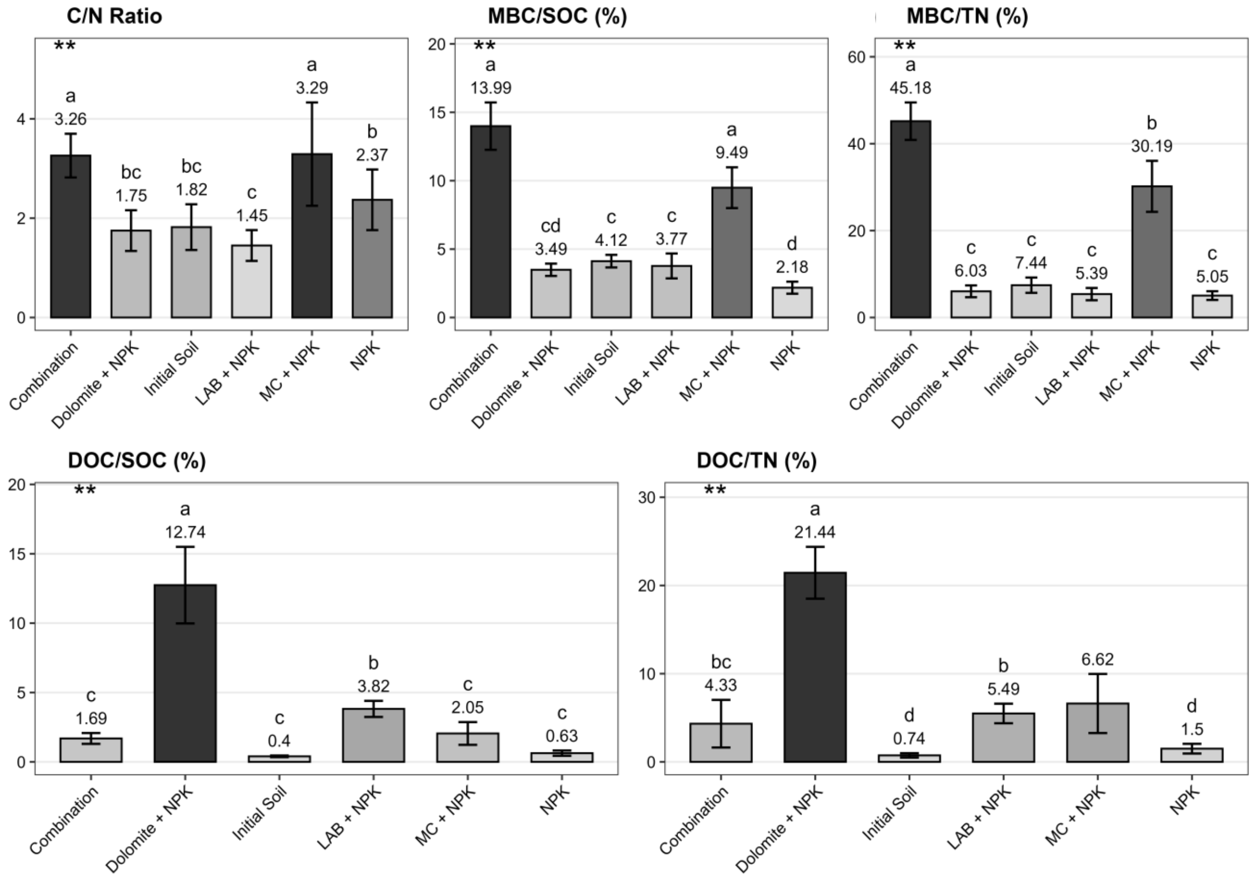

Figure 4. Soil carbon-nitrogen stoichiometric ratios and microbial efficiency indicators under organic-mineral amendments in simulated drought with letter symbol which is mean numbers in the same bar followed by different letters indicate significantly different according to duncan test at the 5% level, while numbers in the same bar followed by the same letter indicate not significantly different according to tukey's test at the 5% level, and **: Very significant at $p<0.01$ (one-way ANOVA)

Soil physicochemical response to integrated amendment treatments under drought stress with insights from redundancy analysis

Redundancy Analysis (RDA) was used to visualize the relationship between treatments and the main physicochemical properties of the soil after a 100-day drought simulation (Figure 5). The first two RDA axes explain 67.3% of the total data variation, with soil moisture (SM; R^2=0.951), bulk density (BD; R^2=0.783), and soil organic carbon (SOC; R^2=0.844) as the most influential variables. The RDA1 axis represents the fertility and recovery gradient, with strong positive values correlated with increased SOC (vector 0.840) and TN (vector 0.355). Conversely, negative values indicate a strong association with high BD (vector -0.885) and SM (vector -0.623).

The position of treatments on this diagram illustrates a clear recovery pattern. Initial Soil, which did not undergo drought simulation, is isolated in the lower left quadrant, characterized by high moisture and density. Conversely, compost-based treatments (Combination and MC+NPK) cluster on the far-right side, indicating their success in enhancing soil fertility by increasing SOC and TN. Treatments relying solely on inorganic inputs or microorganisms have not shown success and remain on the negative side or in the middle of the RDA1 axis.

These findings confirm that adding organic matter is the most effective strategy for restoring degraded soil under drought conditions (Lal 2020). These results are consistent with Morales-Salmerón et al. (2024), who reported that organic amendments can improve soil physical and chemical properties, even under drought conditions. Additionally, the effectiveness of the combined treatment in this study supports the importance of integrating nutrient management into soil restoration strategies (Lal 2015). Compared to studies on other post-mining soils, these findings align with the results of Creamer et al. (2024), who stated that the combination of compost, dolomite, and microorganisms can significantly increase organic carbon through mechanisms such as pH improvement, soil structure enhancement, nutrient supply, and organic matter accumulation. These findings confirm that supplying sufficient organic matter is the most critical factor for restoring the physical and chemical properties of degraded soil due to tin mining and for building its resilience to drought.

Carbon pool recovery and microbial activation in degraded tin-mined soils under drought with integrated amendment treatments based on Redundancy Analysis

A second Redundancy Analysis (RDA) was conducted to explore the relationships between the amendment treatments and soil carbon pools (Figure 6). The results were significantly ($p<0.05$) shaped by three main variables: Dissolved Organic Carbon (DOC; R2=1.000), Microbial Biomass Carbon (MBC; R2=0.963), and Soil Organic Carbon Stock (SOCS; R2=0.959). The model was highly robust, with the first two axes explaining 93.4% of the total data variation.

The RDA1 axis represents a clear gradient in carbon sequestration and biological activation. The positive side of this axis showed a strong correlation with increased SOCS (vector=0.978) and MBC (vector=0.978), which are key indicators of successful soil recovery. The compost-based treatments (Combination and MC+NPK) plotted firmly on this positive side, indicating their effectiveness. This success is underpinned by the quality of the compost used, which provided a substantial carbon input (SOC=24.06%) with a favorable C/N ratio (Table 1), acting as a stable source of energy and nutrients to support microbial life and long-term carbon storage, especially under stress conditions (Bogati and Walczak 2022; Bai et al. 2023). Furthermore, the Combination treatment demonstrated a synergistic effect between the organic, biological, and inorganic ameliorants in stimulating microbial life; other studies on mine-reclaimed soils have also reported that combined ameliorant applications can increase microbial biomass carbon up to five-fold (Yun et al. 2016). Moreover, other interactions from this combination can also improve soil fertility and carbon reserves (Nayak et al. 2020).

Conversely, the negative side of the RDA1 axis, which correlated with high DOC, included the Initial Soil and all treatments without compost. This indicates a failure to build stable or living carbon pools. The Dolomite+NPK treatment presented an interesting case of system dysfunction. Although this treatment generated the highest levels of DOC, MBC accumulation remained low. This suggests that while dolomite's effect on pH solubilized existing organic matter, the microbial community could not utilize this labile carbon, likely due to persistent water stress (Qu et al. 2023). Additionally, the supplied Ca^{2+} ions can form organo-mineral bridges, physically trapping and protecting DOC from microbial decomposition and preventing its conversion into microbial biomass (Maftukhah et al. 2023; Sae-Tun et al. 2025). Therefore, this analysis concludes that an effective recovery strategy must not only add carbon to the soil but also actively support its transformation into living microbial biomass. Merely increasing a transient pool like DOC, without a corresponding biological uptake, does not signify functional recovery. The synergistic integration of organic matter with other ameliorants proved to be the determining factor in building a healthy and biologically active soil carbon system.

Microbial stoichiometry and C–N use efficiency in degraded tin-mined soils revealed by Redundancy Analysis under drought with integrated amendment treatments

A third Redundancy Analysis (RDA) was conducted to investigate how the amendments influenced microbial nutrient use efficiency, based on key stoichiometric ratios (Figure 7). The model was highly representative, explaining 86.2% of the total data variation. Data placement is most strongly influenced by key ratios such as MBN/TN (R^2=0.989), DOC/SOC (R^2=0.979), and the corrected MBC/SOC ratio (R^2=0.867).

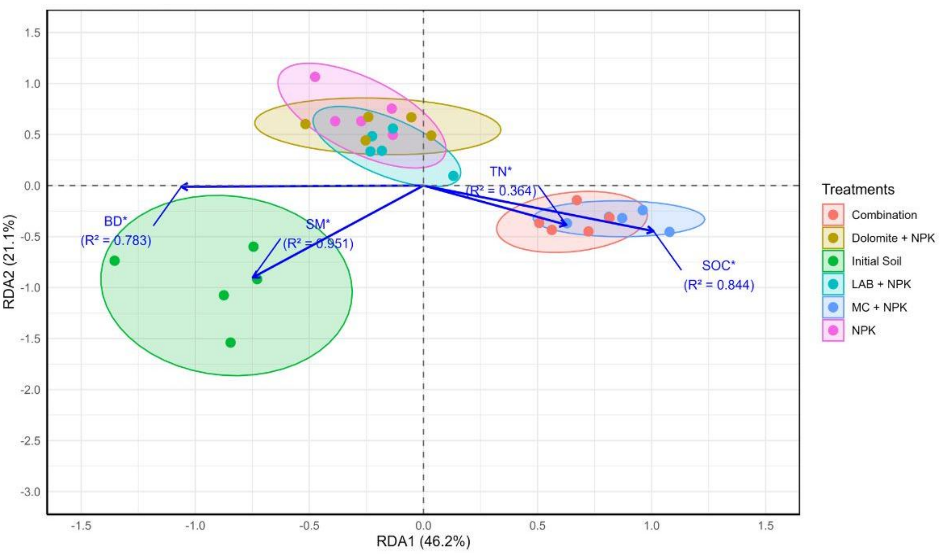

Figure 5. Redundancy Analysis (RDA) showing the influence of organic-mineral amendments on soil physical and chemical properties in degraded tin-mined soils under drought conditions. R^2: Coefficient of determination, *: Significant at $p<0.05$

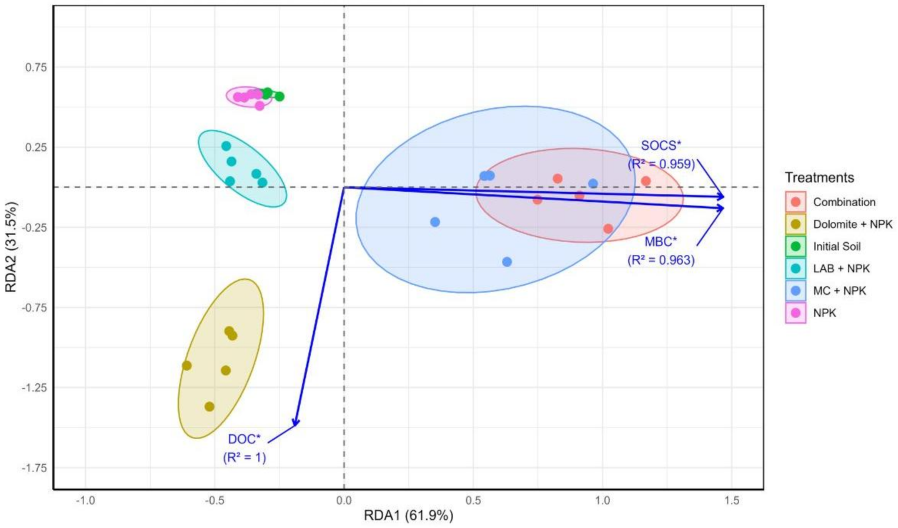

Figure 6. Redundancy Analysis (RDA) of soil carbon pools and microbial biomass as influenced by organic-mineral amendments in degraded tin-mined soils under drought conditions. R^2: Coefficient of determination, *: Significant at $p<0.05$

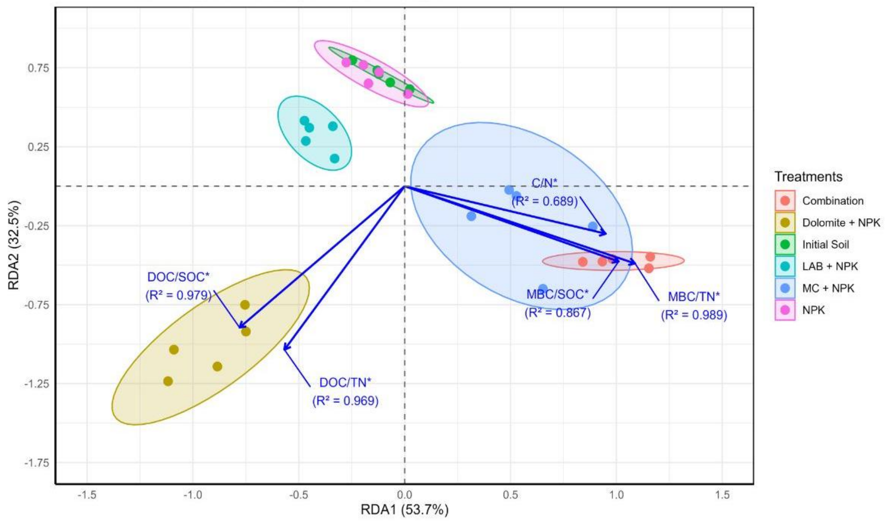

Figure 7. Redundancy Analysis (RDA) of soil carbon–nitrogen stoichiometric ratios under different organic-mineral amendment treatments in drought-affected tin-mined soils. R^2: Coefficient of determination, *: Significant at $p<0.05$ level

The RDA1 axis separated the treatments based on a gradient of microbial efficiency. The positive side of this axis, representing high efficiency, correlated strongly with ratios such as MBC/TN (vector=0.842) and MBC/SOC (vector=0.907). Combination treatment is placed in the extreme positive quadrant, demonstrating its absolute superiority. This indicates a highly efficient system where new carbon and nitrogen inputs are rapidly channeled into living microbial biomass rather than being lost or stored in non-living forms. The MC+NPK treatment also showed high efficiency, confirming the vital role of compost. This synergy likely occurs because the amendments simultaneously address multiple soil limitations, such as the compost provides a complex carbon substrate and habitat (Wang et al. 2022), and the inorganic fertilizer offers readily available nutrients for microbes (Aberagi et al. 2024), and the dolomite optimizes soil pH for broader microbial activity (Ndabankulu et al. 2022).

Conversely, the negative side of the RDA1 axis, associated with inefficiency or system dysfunction, correlated with high DOC/SOC and DOC/TN ratios. The Dolomite+NPK treatment was a clear outlier on this side. This indicates a system imbalance characterized by the accumulation of labile carbon without a corresponding increase in microbial biomass, a clear sign of decoupling between carbon availability and microbial uptake. This dysfunction can be mechanistically explained: while the effect of dolomite on pH solubilized organic matter, the supplied divalent Ca^{2+} ions also act as cationic bridges between negatively charged clay surfaces and organic molecules (Holland et al. 2018). This process results in flocculation and the formation of micro-aggregates, physically protecting the DOC within these structures and rendering it inaccessible to extracellular microbial enzymes (Sae-Tun et al. 2025).

Meanwhile, the NPK and LAB+NPK treatments are plotted near the origin, signifying their low effectiveness. Previous studies have shown that NPK application without organic matter can lead to nitrogen losses of over 35%, compared to only 20-24% when organic matter is present (Duan et al. 2016), and can suppress dehydrogenase activity by up to 88-93% in sandy soils during drought periods (Siebielec et al. 2020). Consequently, without an organic substrate, the efficiency of microbial carbon and nitrogen use becomes limited (Pan et al. 2014). Therefore, the NPK and LAB+NPK treatments failed to enhance microbial functions, such as carbon use efficiency, under drought conditions due to poor nitrogen retention and limited carbon substrate (Bao et al. 2024).

Overall, this analysis confirms that restoring the biological resilience of degraded soil requires an approach that addresses biochemical, physical, and nutritional limitations simultaneously. The multi-ameliorant synergy in the Combination treatment proved to be the most effective strategy for building a healthy and responsive soil microbial system.

Relationships among soil physical, soil carbon pools, nutrient availability, and microbial activity under simulated drought

A Pearson correlation analysis was performed on the treated soils (excluding the initial soil) to examine the linear relationships between physical, chemical, and biological parameters following amelioration and drought treatments (Figure 8). The analysis revealed distinct patterns of association among key soil variables. Bulk Density (BD), as an indicator of soil density, showed a strong negative correlation with key soil health indicators such as soil organic carbon (SOC; r=-0.689) and microbial biomass carbon (MBC; r=-0.618). BD also showed a moderate negative correlation with soil moisture (SM; r=-0.572), which indicates that denser soils retain less water. Conversely, SOC was strongly and positively correlated with SM (r=0.841) and MBC (r=0.909). SOC also showed a significant positive correlation with C-use efficiency indices, including the MBC/SOC ratio (r=0.816). MBC itself was positively correlated with the MBC/TN ratio (r=0.774) and the C/N ratio (r=0.655), indicating a close link between carbon availability and nitrogen utilization by microbes.

Total Nitrogen (TN) showed weaker correlations with most parameters, with only moderate positive relationships with SM (r=0.601) and SOC (r=0.583). The C/N ratio was positively related to SOC (r=0.734) and MBC (r=0.655) but was not significantly connected to BD or SM. DOC showed no significant correlation with other parameters but was almost perfectly correlated with its derivative ratio, DOC/TN (r=0.980). The DOC/TN ratio, in turn, did not show a notable relationship with other major soil parameters, indicating that DOC behaved independently from the more stable C and N pools under the experimental conditions.

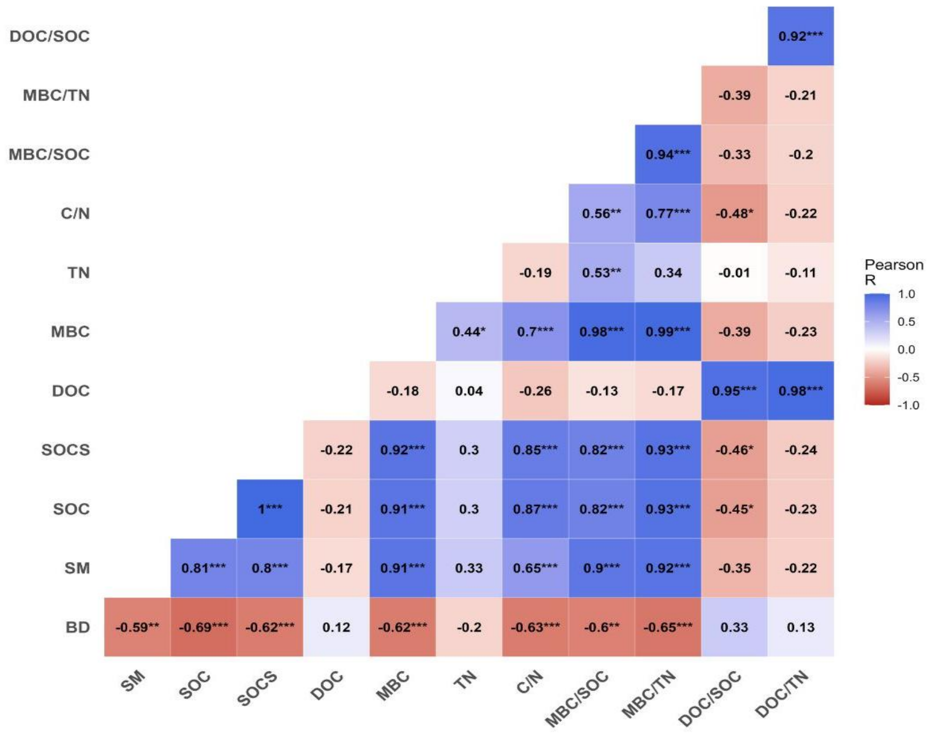

Figure 8. Pearson correlation heatmap among soil physical properties includes BD (Bulk Density) and SM (Soil Moisture). Chemicals include SOC (Soil Organic Carbon), SOCS (Soil Organic Carbon Stock), DOC (Dissolved Organic Carbon), TN (Total Nitrogen), and biological parameters such as MBC (Microbial Biomass Carbon), and stoichiometric parameters under organic-mineral amendment treatments in drought-affected tin-mined soils. The significance indicates the differences with *: p<0.05, **: p<0.01 and ***: p<0.001

The strong negative correlations between BD and major soil health indicators (SOC, MBC, SM) highlight the fundamental role of soil physical structure in controlling biogeochemical processes. A decrease in BD increases soil porosity, thereby enhancing water retention and soil aeration, which creates favorable conditions for microbial growth (Fageria 2012; Özdemir et al. 2022). This interpretation is supported by the positive correlations observed between SM, SOC, and MBC. While a decrease in BD typically promotes oxygen diffusion, studies such as Gui et al. (2023) have reported cases where drier conditions paradoxically increased microbial activity. In contrast, our findings show that under drought conditions, the negative effects of water limitation were more dominant than the potential benefits of increased aeration, which confirms that maintaining a low BD is critical to sustaining microbial communities under water stress (Liu et al. 2023; Kang et al. 2024).

Soil Organic Carbon (SOC) was a primary driver of soil health, showing strong positive correlations with SM and MBC. This indicates that higher organic matter content directly supports better moisture retention and fosters greater microbial biomass. The significant relationship between SOC and microbial C-use efficiency indices (MBC/SOC, MBC/TN) underscores the role of organic matter in sustaining active microbial pools. Furthermore, the positive relationship between SOC and the C/N ratio indicates that soils with higher organic carbon content tend to support the accumulation of carbon stocks and the growth of microbial biomass (Li et al. 2024).

Microbial Biomass Carbon (MBC) has been confirmed as a pivotal factor in nutrient cycling. The strong correlation of MBC with its efficiency ratios (MBC/SOC and MBC/TN) emphasizes the central role of microbial biomass in the C and N cycles (Das et al. 2023), consistent with Melendez et al. (2020). The increase in MBC can be faster than that of SOC, thereby directly enhancing the soil's biological efficiency. The positive MBC–MBC/TN relationship occurs because sufficient TN provides the nitrogen needed for microbial growth (Jia et al. 2005), which indicates a high efficiency in N utilization for biomass formation. In contrast, TN's weak correlation with other variables is consistent with its nature as a static indicator. The strong relationship between TN and microbial biomass reported by Parajuli et al. (2024), supports this view, showing that nitrogen dynamics are better reflected by microbial processes such as mineralization and immobilization than by total N content (Čapek et al. 2021). Additionally, the C/N ratio also correlated positively with microbial biomass, indicating the crucial role of microbial immobilization in maintaining biomass pools under drought conditions, thereby demonstrating the resilience of soil ecosystems. Li et al. (2021) showed that the soil C/N ratio increases MBC and the nitrogen immobilization rate due to greater carbon availability for microbes. In the context of drought, Sun et al. (2020b) found that the microbial biomass C/N ratio increased due to a greater decrease in microbial nitrogen compared to carbon, driven by the dominance of more drought-resistant fungi, thereby maintaining MBC.

The absence of a significant correlation between DOC and other major soil parameters (except DOC/TN) highlights its labile and transient nature (Campbell et al. 2022). As a highly bioavailable carbon source, DOC is consumed and mineralized rapidly by microbes, resulting in temporal fluctuations that may not align with more stable C pools (SOC) or Microbial Biomass Carbon (MBC) at a given sampling time (Shen et al. 2021). Under drought conditions, DOC released through microbial stress or lysis may persist longer in the soil due to reduced leaching, but its utilization is limited when microbial activity is impaired by water scarcity (Harrison et al. 2025). Furthermore, the drought issue also decreases DOC due to the accumulation of broken soil aggregates and the death of sensitive microbes (Dong et al. 2021). Additionally, the mobilization of particle-bound DOC triggered by an increase in pH after dolomite application (Filep and Rékási 2011) may explain the independent behavior of DOC in our dataset.

These correlations confirm that improving the soil's physical condition, primarily through organic matter inputs, is the key point for enhancing carbon storage, biological health, and C-use efficiency by microbes. The close linkage between physical, chemical, and biological properties underscores the importance of integrated management strategies for rehabilitating degraded soils while also contributing to climate change mitigation.

This study's conclusion indicates that an integrated, multi-ameliorant approach combining municipal compost with dolomite, LAB, and NPK fertilizer is the most effective and synergistic strategy. This research offers three key implications for land restoration in arid or drought-prone environments. First, the addition of a substantial organic matter base is a necessary prerequisite for recovery. Treatments without compost did not significantly improve soil health significantly, indicating that merely applying inorganic fertilizers or microbial inoculants to carbon-depleted soils is an ineffective strategy. Organic matter is essential for rebuilding the soil's physical structure and providing the energy substrate needed to reactivate biological functions. Furthermore, true soil improvement should be measured by functional recovery, not just nutrient enrichment. For example, the dolomite treatment increased dissolved organic carbon but did not stimulate microbial uptake, resulting in a dysfunctional system. The success of this combination treatment depends on its ability to improve microbial carbon-use efficiency, demonstrating that a healthy soil actively cycles nutrients rather than passively holds them. Finally, this study highlights a feasible pathway for building soil resilience against climate stress. The synergistic effects of this combined treatment created a robust soil system that could not only store more carbon but also maintain a healthy microbial community during severe drought. Therefore, we recommend that land rehabilitation programs adopt a holistic, multi-ameliorant-based approach, supplemented with appropriate amendments, to accelerate long-term ecological restoration and improvement in degraded, drought-prone tin post-mining landscapes.

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