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The role of red mud and cow manure for sustainable post-gold mining land rehabilitation

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ABSTRACT

The detrimental ecological impact of unauthorized gold mining in Indonesia is significantly profound, notably apparent in the nutrient-deficient, sandy soils with low pH resulting from the process. These conditions contribute to considerable land productivity decline, especially in West Kalimantan. In response to this challenge, the current study proposes an inventive approach for soil reclamation using red mud residue, derived from bauxite ore extraction, and cow manure as restorative elements. This research delves into a novel soil restoration technique that employs red mud waste (a residual from ore refinement) in conjunction with cow manure as ameliorative agents. A distinct amalgamation of 0.2 kg of red mud and 3 kg of cow manure (T2R3) showcased superior results. The incorporation of this blend resulted in a significant increase in soil pH by 0.93 units, an increase in macronutrient content ranging from 82.84%-503.07%, and plant growth (plant height and stem diameter) increased between 32.85%-54.31% in the treatment with 0.2 kg of red mud and 3 kg of cow manure (T2R3) compared to the lower treatment of 0.1 kg of red mud and 1 kg of cow manure (T1R1). These changes were evident, indicating improved soil fertility and the potential for increased crop yield.

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1. INTRODUCTION

Unauthorized gold mining within Indonesia inflicts significant detriments upon the state, with these impacts exacerbated by an expanding mined land area (Saputra et al., 2023). Critical factors contributing to these state losses include a lack of public cognizance concerning the enduring impacts of mining and a limited scope of livelihood alternatives for the local community (Hasibuan et al., 2022). These elements underscore the essentiality of land rehabilitation, not only as a strategy to enhance land productivity, but also as a means to provide alternative livelihoods thereby curtailing the expansion of gold mining.

Post-gold mining landscapes typically experience critical degradation due to the loss of topsoil (Ofosu & Sarpong, 2023; Timsina et al., 2022) and a deficiency of essential nutrients (Punia & Bharti, 2023), resulting in considerable land unproductivity (Achina-Obeng & Aram, 2022; Ocampo & Schmitz, 2023; Worlanyo & Jiangfeng, 2021). This plight is markedly reflected within West Kalimantan, where post-illegal gold mining spans an expansive 6,613 ha distributed across 267 locations in eleven regencies (Sulakhudin et al., 2017). The persistent presence of illegal gold mining significantly fuels land degradation rates (Caballero Espejo et al., 2018; Daniell et al., 2019; Ramirez et al., 2020). This degradation manifests as sandy soil, characterized by low water retention capacity and high light intensity due to scarcity of vegetation, resulting in elevated soil surface temperatures and limited productivity for plant growth (Román-Dañobeytia et al., 2021; Tollefson, 2020).

Rehabilitation strategies subsequent to mining activities are critically vital for the reinstatement of ecological processes, preventing further environmental deterioration, adhering to legal stipulations, and advancing sustainable environmental preservation (Eldridge et al., 2022; Mentis, 2020). The methodologies adopted advocate for the reversion of gold mining locales to their initial state, revitalizing soil productivity, and recalibrating hydrological and nutrient dynamics (Suswati & Denashurya, 2023; Worlanyo & Jiangfeng, 2021).

However, efforts to repurpose post-gold mining land as a natural growing medium for plants face challenges that curtail land productivity, particularly poor chemical properties such as nutrient deficiency and low soil pH (Asmara, 2020). Strategies to enhance the productivity of post-gold mining land, including the application of lime, organic fertilizers, and inorganic fertilizers, have been implemented to elevate soil pH and provide nutrients for soil fertility improvement (Silveira & Kohmann, 2020; Verma et al., 2020). Nonetheless, these efforts have yet to achieve significant improvement in soil fertility as indicated by low crop yields.

This research aims to determine the effect of the combination of red mud dosage and cow manure fertilizer that can increase nutrient availability and the highest growth of corn plants on post-gold mining land. Additionally, this approach serves as a practical solution to contribute to food security. The study's pragmatic approach addresses economic, social, and environmental challenges associated with gold mining and makes a significant contribution to the global discussion on effective land rehabilitation techniques. Implementing these techniques brings multiple benefits to the environment and local communities (Ahirwal & Pandey, 2021; Worlanyo & Jiangfeng, 2021).

Red mud residue, an aftermath of the bauxite ore refinement yielding alumina, demonstrates an amplified capacity to elevate soil pH and intensify nutrient conservation when combined with organic substrates, specifically cow manure fertilizer (Di Carlo et al., 2019; Xu et al., 2021). Moreover, this technique bestows economic gains, fortifies food security, curtails production expenditures, spawns novel entrepreneurial avenues, and diminishes the ecological detriment resulting from inordinate limestone extraction (Suswati & Denashurya, 2023; Wang et al., 2021).

Red mud emerges as a residue from the Bayer method employed in refining bauxite ore, wherein sodium hydroxide is subjected to elevated temperatures and pressures to yield high-grade Aluminum (Pasechnik et al., 2020; Zhou et al., 2023). To employ red mud waste as a planting medium, an amelioration process, utilizing organic materials such as cow manure fertilizer, is essential to improve its quality. This process transforms the surface properties of iron oxides in red mud from predominantly positive charge to predominantly negative charge, enhancing cation retention capacity (Motsi et al., 2019; Wang et al., 2021). Organic materials chelate heavy metals present in red mud and post-gold mining soil, rendering their utilization environmentally safe (Awad et al., 2021; Qureshi et al., 2020). Furthermore, these organic materials enhance soil aggregate stability, augment water absorption capacity, improve soil cation exchange capacity, and provide carbon for soil microorganism life, thus optimizing soil fertility and serving as a nutrient source for plants (Farooqi et al., 2023; Rahman et al., 2020).

It is imperative to conduct research on sustainable post-gold mining land rehabilitation, with the goal of minimizing losses arising from land degradation and maximizing land productivity. A suitable amelioration technology that aligns with site conditions can play a key role in enhancing soil fertility and land quality (Feng et al., 2023; Setiawan et al., 2021). Consequently, judicious stewardship of post-mining terrains is essential in attenuating detrimental environmental repercussions and advocating for sustainable mining protocols. The governance's mandate, via the promulgation of rigorous directives, assumes profound importance, especially considering the overarching environmental ramifications of such endeavors.

2. MATERIAL AND METHODS

This study, spanning eight months from March to November 2021, employed polybags on an experimental tract of land at the Faculty of Agriculture, University of Tanjungpura. Sampling places were located for its post-gold mining landscapes in Bengkayang Regency. Red mud originates from the Alumina factory of PT. ICA in Sanggau Regency, while cow manure fertilizer comes from cattle farming in Kuburaya Regency. Analytical processes concerning soil chemistry and fertility were overseen by the Soil Chemistry and Fertility Laboratory within the University of Tanjungpura.

Chemical analysis revealed that the upper soil stratum (0-30 cm) was characterized by a sandy texture (comprising 87.50% sand, 12.57% silt, and 0.20% clay). Furthermore, it exhibited high acidity (pH 3.34), very low organic carbon content (0.21%), minimal total Nitrogen content (0.03%), low levels of available Phosphorus (11.83 ppm), negligible quantities of exchangeable Potassium (0.03 cmol(+) kg^{-1}), Calcium (0.26 cmol(+) kg^{-1}), Magnesium (0.16 cmol(+) kg^{-1}), Sodium (0.03 cmol(+) kg^{-1}), extremely low base saturation (11.09%), and a low cation exchange capacity (4.33 cmol(+) kg^{-1}).

2.1. Ameliorants Mixture Preparation

In the preparation of the ameliorants mixture, the process included drying, sieving through a 0.2 cm sieve, and subsequent weighing in accordance with the specified treatment requirements. Analyses indicated that the red mud had a clayey texture (comprising 10.87% sand, 52.55% silt, and 36.58% clay), high alkalinity (pH 10.14), minimal organic carbon content (0.18%), low total Nitrogen content (0.03%), low available Phosphorus (0.52ppm), and a low CEC (5.37 cmol(+) kg^{-1}). Cow manure analysis disclosed a high pH of 6.6, high organic carbon content (34.22%), substantial total Nitrogen content (14.80%), and total Phosphorus (0.17%).

2.2. Experimental Design and Treatments

The study employed a Completely Randomized Design (CRD) featuring nine treatment levels, each replicated five times, culminating in a total of 45 experimental units. Treatments that incorporated various proportions of red mud and cow manure fertilizer are displayed in Table 1.

Table 1. Treatments that Incorporated Various Proportions of Red Mud and Cow Manure Fertilizer

Treatment	Red Mud (kg)	Cow Manure (kg)
T1R1	0.1	1
T1R2	0.1	2
T1R3	0.1	3
T2R1	0.2	1
T2R2	0.2	2
T2R3	0.2	3
T3R1	0.3	1
T3R2	0.3	2
T3R3	0.3	3

2.3. Implementation of the Study

In the experimental implementation, each polybag was filled with 12 kg of post-gold mining soil amalgamated with the specified ratios of ameliorants mixture. A base fertilizer (Urea) was applied in rates of 500 kg.ha^{-1} (10 g/polybag), Super Phosphate (SP36) 400 kg.ha^{-1} (8 g/polybag), and Kalium klorida (KCL) 300 kg.ha^{-1} (6 g/polybag). Following a month-long incubation period, corn was planted in each polybag, with measurements of plant height (base of the stem to the tip of the longest leaf) and stem diameter (at the base of the stem) taken at the peak vegetative phase (56 days after planting).

2.4. Soil Sample Procurement and Analysis

Following the completion of the incubation process, soil samples were sourced from the designated polybags to undergo laboratory inspection. This investigative process involved assessing the soil's pH levels using buffer solutions marked at pH 7.0 and 4.0, identifying its organic carbon concentration via the Walkey and Black wet oxidation procedure, evaluating total Nitrogen content with the Kjeldahl approach, quantifying available Phosphorus through the Bray-I technique, and determining levels of exchangeable cations (NH_4Oac 1 N pH 7 extraction procedure). Additionally, the CEC was gauged using the Indophenol Blue method. Ammonium Acetate (1M NH_4OAc) (pH 7.0) was used to extract exchangeable Ca, K Mg and Na. Potassium content was determined by flame photometer (Moreira & Fageria, 2009). Ethylenediaminetetraacetic acid (EDTA) titration was done to measure Ca and Mg from the soil solution. CEC in (cmol(+) kg^{-1}) and percentage base saturation BS (V%) were calculated following the methods (Blanchet et al., 2017; Yeshaneh, 2015).

The data were analyzed using the Statistical Package for Social Science (SPSS) software (Josephat Ligate et al., 2018). Quantitative evaluations were conducted resulting the F-test and Duncan's Multiple Range at a confidence interval of 5% (Floro et al., 2017).

3. RESULTS

3.1. Post-Incubation Soil Chemical Characteristics

Table 2 highlights that the conjunctive application of ameliorants mixture markedly alters the chemical characteristics of soil post-gold mining, encapsulating parameters such as soil pH, organic carbon (C) concentrations, total Nitrogen (N), available Phosphorus (P), and exchangeable cations like Potassium (K), Calcium (Ca), Magnesium (Mg), Sodium (Na), in addition to cation exchange capacity (CEC) and base saturation (BS).

3.1.1. Soil pH Reaction

Table 2 presents that the mixture treatment with 0.3kg of red mud and 3 kg of cow manure (T3R3) exhibited a significant distinction from other treatments regarding soil pH post-incubation, barring treatments T3R1 and T3R2. Notably, T3R3 possessed the apex pH value of 7.40, signifying a 1.3 units elevation when juxtaposed to the treatment with a lesser quantity of 0.1 kg red mud and 1kg cow manure (T1R1).

3.1.2. Organic Carbon in Soil

Table 2 delineates that the mixture treatment of 0.2kg red mud and 3kg cow manure (T2R3) markedly deviated from other treatments in relation to soil organic carbon (C-org) after the incubation phase. This treatment manifested the zenith C-org value of 3.68%. Furthermore, the aforementioned treatment markedly bolstered the soil C-org by 65.77% compared to T1R1. Conversely, the highest application level, namely T3R3, induced a substantial decrement in soil C-org to 3.10%.

3.1.3. Soil's Total Nitrogen

The data from Table 2 illustrates that the mixture treatment of 0.2 kg red mud and 3 kg cow manure (T2R3) exhibited significant variance from its counterparts in terms of total soil Nitrogen (N-total) post-incubation, with an acme N-total value of 1.82%. Additionally, there was an upswing in N-total by 50.41% vis-à-vis T1R1. Yet, the elevated application combination, T3R3, culminated in a notable diminution of N-total to 0.73%.

3.1.4. Soil's Available Phosphorus

Table 2 posits that T2R3, comprising 0.2 kg of red mud and 3kg cow manure, surpassed other treatments in terms of available Phosphorus (P) post-incubation, except for T3R1, T3R2, and T3R3. This mixture treatment conspicuously augmented available soil P by 235.55% relative to T1R1, whereas the treatment T3R3 indicated a declination trend to 34.79 ppm.

3.1.5. Exchangeable Potassium in Soil

The mixture treatment of 0.2kg red mud and 3 kg cow manure (T2R3) in Table 2 was discerned to have the pinnacle exchangeable potassium (Exch. K) value of 1.88 cmol(+) kg^{-1}, differing substantially from other treatments post-incubation. This represented an enhancement by 108.89% compared to T1R1. Yet, the T3R3 mixture treatment signified a decline in Exch. K to 1.39 cmol(+) kg^{-1}.

3.1.6. Exchangeable Calcium in Soil

Table 2 indicates that the mixture treatment T2R3 significantly surpassed others in terms of exchangeable calcium (Exch. Ca) following incubation, exhibiting an exponential increment by 503.07% vis-à-vis T1R1. However, the highest application, T3R3, recorded a decrease in Exch. Ca to 19.11 cmol(+) kg^{-1}.

3.1.7. Exchangeable Magnesium in Soil

The mixture treatment T3R3, as per Table 2, substantially escalated the exchangeable magnesium (Exch. Mg) levels, achieving the zenith value of 4.06 cmol(+) kg^{-1}. This treatment differed significantly from others post-incubation, save for T3R1 and T3R2. Relative to T1R1, there was an amplification by 99.02% in the soil's Exch. Mg.

Table 2. Impact of the integrated red mud and cow manure fertilization on chemical characteristics of soil post-gold mining

Treatment	Analysis Results of Soil After Incubation									
	Soil pH	Organic C (%)	N-Total (%)	Available P (ppm)	Exch. K (cmol(+) kg^{-1})	Exch. Ca (cmol(+) kg^{-1})	Exch. Mg (cmol(+) kg^{-1})	Exch. Na (cmol(+) kg^{-1})	CEC (cmol(+) kg^{-1})	BS (%)
T1R1	6.10f	2.22f	1.21f	10.69g	0.90d	4.24e	2.04e	2.23e	8.78e	107.44e
T1R2	6.11f	2.41e	1.29d	17.84f	0.93d	4.90d	2.69d	5.25d	10.50d	131.14d
T1R3	6.21e	2.76d	1.26d	25.87e	1.39c	12.53c	3.20c	5.85c	12.23c	187.82c
T2R1	6.26e	2.99c	1.38c	31.47d	1.34bc	17.91b	3.42bc	7.94b	12.53bc	244.29b
T2R2	6.51d	2.98c	1.51b	33.40c	1.66ab	20.08b	3.50bc	8.15ab	12.74ab	262.09b
T2R3	7.03c	3.68a	1.82a	35.87b	1.88a	25.57a	3.73bc	8.21ab	13.34a	295.28a
T3R1	7.31b	3.18b	1.28d	34.82b	1.39bc	19.42b	3.96a	8.39a	13.14a	250.76b
T3R2	7.35b	3.20b	0.76e	34.81b	1.40bc	19.21b	3.98a	8.47a	13.27a	249.21b
T3R3	7.40b	3.10b	0.73e	34.79b	1.39bc	19.11b	4.06a	8.48a	13.4a	248.73b

Remarks : Values denoted by identical letters suggest no notable variation within the same row.

Table 3. Effect of the joint red mud and cow manure fertilization on the height and stem diameter of maize in soil after gold mining activities

Treatment	Height (cm)	Stem Diameter (cm)
T1R1	143.18g	15.54e
T1R2	158.48e	19.20d
T1R3	168.34d	22.64b
T2R1	176.14c	21.26c
T2R2	186.10ab	22.78b
T2R3	190.22a	23.98a
T3R1	181.18bc	20.68c
T3R2	167.00d	22.52b
T3R3	151.56f	19.58d

Remarks : Values denoted by identical letters suggest no notable variation within the same row

3.1.8. Exchangeable Sodium in Soil

Table 2 illustrates that T3R3's mixture treatment significantly boosted exchangeable sodium (Exch. Na) in soil, with a peak value of 8.48 cmol(+) kg^{-1}. It stood apart from other treatments post-incubation, excluding T2R2, T2R3, T3R1, and T3R2. This treatment augmented soil Exch. Na by 280.27% compared to T1R1.

3.1.9. Soil Cation Exchange Capacity

Table 2 elucidates that the mixture treatment T2R3 achieved the pinnacle CEC value of 13.34 cmol(+) kg^{-1}, markedly differing from its counterparts post-incubation. This implied an enhancement by 51.94% relative to T1R1. However, the T3R3 mixture treatment showcased a near-equivalent CEC value of 13.4 cmol(+) kg^{-1}.

3.1.10 Soil Base Saturation

The mixture treatment of T2R3, according to Table 2, exhibited the paramount base saturation (BS) value of 295.28%. This treatment deviated substantially from others in terms of soil base saturation post-incubation, presenting an escalation by 174.83% vis-à-vis T1R1. Conversely, T3R3 manifested a decrement in soil base saturation, reaching 248.73%.

3.2 Maize Plant Morphology

Table 3 underscores the profound effect of ameliorants mixture on maize growth metrics, notably concerning plant height and stem diameter.

3.2.1 Plant Stature

As depicted in Table 3, the mixture treatment of 0.2 kg red mud and 3 kg cow manure (T2R3) significantly elevated the height of maize plants, registering a zenith value of 190.22 cm. This outcome markedly deviated from other mixture treatments in terms of maize plant height post-incubation, save for the T2R2 mixture treatment which combines 0.2kg red mud and 2 kg cow manure. A salient increase of 32.85% in maize plant height was observed when compared to the treatment with the minimal red mud and cow manure application, specifically the blend of 0.1kg red mud and 1kg cow manure (T1R1). Yet, amplifying the mixture treatment to its utmost level, encompassing 0.3 kg red mud combined with 3kg cow manure (T3R3), culminated in a significant decline in plant height, recording a value of 151.56 cm.

3.2.2 Stem Diameter

Table 3 indicates that the mixture treatment integrating 0.2 kg of red mud with 3 kg of cow manure (T2R3) notably augmented the diameter of maize plant stems, achieving a pinnacle value of 23.98 cm. This finding significantly diverged from other mixture treatments concerning the maize plant stem diameter after the incubation period. The aforementioned mixture treatment bolstered the maize stem diameter substantially by 54.31% compared to the minimum red mud and cow manure mixture, which is the combination of 0.1 kg red mud and 1 kg cow manure (T1R1). Conversely, enhancing the mixture treatment to its highest proportion, entailing 0.3 kg red mud amalgamated with 3 kg cow manure (T3R3), resulted in a pronounced reduction in stem diameter, reaching 19.58 cm.

4. DISCUSSION

The incorporation of ameliorants mixture, particularly the blend of 0.2 kg red mud and 3 kg cow manure (T2R3), demonstrated a substantial enhancement in soil parameters such as exchangeable Calcium (Exch. Ca), exchangeable Potassium (Exch. K), available Phosphorus (P), total soil

Nitrogen (N), base saturation (BS) and cation exchange capacity (CEC), as documented by several studies (Abure, 2022; Bouajila et al., 2023). Nonetheless, the paramount application, that is, red mud combined with cow manure (T3R3), culminated in a notable decline in the aforementioned parameters while simultaneously escalating soil pH, exchangeable magnesium (Exch. Mg), and exchangeable sodium (Exch. Na) (Neina, 2019).

The increase in soil total nitrogen (N-Total) is influenced by the decomposition process of soil organic carbon (3.68%) by microorganism activity in the decomposition process of organic matter, which increases at neutral soil pH (7.03), as indicated by several researchers (Bai et al., 2021; Daly et al., 2021). The importance of soil pH in microbial growth is underscored by the optimal range of 6.5-7.5. Additionally, the degradation of organic matter plays a pivotal role in determining soil N concentrations (Chertov et al., 2017; Wang et al., 2021). A decline in total soil N at the zenith application of the mixture was linked to a reduction in organic carbon levels. The organic matter's quality and abundance govern the N yield from decomposition (Chang et al., 2020; Grzyb et al., 2021). Table 4 delineates a marked correlation between total N and parameters such as soil pH and organic carbon.

The increase in available Phosphorus was attributed to the neutral soil pH (7.03), which prevented the fixation of phosphate ions by base cations in the soil solution(Ashrafi et al., 2023; Golia & Diakoloukas, 2022). Additionally, the increase in organic carbon enhanced the solubility of Phosphate and micronutrients through the release of organic acids during organic matter decomposition (Gondal et al., 2021; Gong et al., 2021; Johan et al., 2021). Organic matter can enhance CEC with an increasing soil pH, thereby improving soil nutrient availability (Um-e-Laila et al., 2021), including an increase in Phosphorus availability for plants (Gao et al., 2019; Gmach et al., 2020). However, the highest application of red mud + cow manure decreased available P due to the increased soil pH (7.40), which led to increased base cation solubility, particularly Mg and Na ions, resulting in the precipitation of Phosphate with less soluble Mg and Na compounds. The higher the free Mg and Ca ions, the greater the Phosphate adsorption and reduced P availability. Table 4 shows a highly significant correlation between available P and soil pH, organic carbon, exchangeable K, exchangeable Ca, exchangeable Mg, and exchangeable Na, with correlation coefficients (r) for pH=0.90**, organic carbon=0.91**, exchangeable K=0.82**, exchangeable Ca=0.98**, exchangeable Mg=0.92**, and exchangeable Na=0.98**.

The observed elevation in exchangeable K can be attributed to the prominent occurrence of clay minerals in the red mud introduced, functioning as a viable repository for soil K (Buss et al., 2022; Zhang et al., 2020). The reduction in exchangeable K, following the maximal application of red mud combined with cow manure, is attributed to the marked ascent in soil pH (7.40) and the paramount surge in Mg ions in the soil medium (4.06 cmol(+) kg^{-1}), which could potentially supplant K in the soil composition. The upswing in exchangeable Ca is tied to the neutral pH (7.03) and the apex CEC (13.34 cmol(+) kg^{-1}), pivotal determinants in gauging soil exchangeable Ca. Table 4 delineates that exchangeable K maintains a nonsignificant relationship with soil pH and exchangeable Mg, indicated by correlation coefficients (r) for pH=0.61tn and exchangeable Mg=0.66tn. Contrastingly, exchangeable Ca exhibits a pronounced correlation with soil pH and CEC, validated by correlation coefficients (r) for pH=0.84** and CEC=0.94*.

In the treatment with the maximal addition of red mud combined with cow manure, there was a marked rise in exchangeable Mg (4.06 cmol(+) kg^{-1}) and exchangeable Na (8.48 cmol(+) kg^{-1}), influenced by an elevated soil pH of 7.40, which facilitated the release of Mg and Na ions into the soil matrix. It is worth noting that Na ions exhibit weak retention by both organic and mineral components of the soil. The observed elevation in CEC has its foundation in its direct association with the clay composition of the soil; a more refined soil texture is indicative of a richer content of clay and organic colloids, thereby leading to an enhanced CEC. This elevation in CEC can also be ascribed to an amplified soil pH value of 7.03 and a predominant presence of organic carbon at 3.68%. The CEC of the soil demonstrates a strong association with its organic matter content, which serves as a primary contributor to the soil's negative charges due to the disassociation of functional groups present in organic acids. It is recognized that the CEC originating from humus can span between 150-300 cmol(+) kg^{-1}. However, with the utmost application of the ameliorants blend, a reduction in CEC was observed, primarily driven by a drop in the soil organic carbon content. Referencing Table 4, there exists a pronounced correlation between the soil's CEC and parameters such as soil pH and organic carbon, with correlation coefficients (r) indicating pH=0.94** and organic carbon=0.96**.

The increase in base saturation (BS) was attributed to the highest levels of base cations, particularly K (1.88 cmol(+) kg^{-1}) and Ca (25.57cmol(+) kg^{-1}), leading to the highest BS of 295.28%. The decrease in BS with the highest red mud and cow manure mixture was due to the decrease in base cations, particularly K (1.39 cmol(+) kg^{-1}) and Ca (19.11 cmol(+) kg^{-1}), resulting in reduced base saturation when base cations decrease. Table 4 shows a highly significant correlation between soil BS and soil pH, K, Ca, Mg, and Na, with correlation coefficients (r) for pH=0.87**, exchangeable K=0.87**, exchangeable Ca=0.98**, exchangeable Mg=0.91**, and exchangeable Na=0.97**.

The observed enhancement in plant growth, signified by a plant height of 190.22 cm and a stem diameter of 23.98 cm, was predominantly guided by the key macronutrients - N, P, and K, which hold a paramount significance in plant development (Abdelaal et al., 2021; Etesami & Adl, 2020; Lin et al., 2021). Conversely, an elevated application of the combination of ameliorants mixture appeared to hinder plant growth, a consequence of diminished concentrations of these pivotal macronutrients (N, P, K). As illustrated in Table 4, there exist substantial to notably significant correlations between metrics of plant height and stem diameter in relation to these macronutrients, with the correlation coefficients (r) delineating total N=0.88**, available P=0.69*, exchangeable K=0.85**, and again for available P=0.78** and exchangeable K=0.88**.

Table 4. Correlation between research observation variables

Variabel	pH Soil	Organic C	N-Total	Available P	Exch. K	Exch. Ca	Exch. Mg	Exch. Na	CEC	BS	Height	Stem Diameter
pH Soil	1											
Organic C	0.95**	1										
N-Total	0.69*	0.75**	1									
Available P	0.90**	0.91**	0.52tn	1								
Exch. K	0.61tn	0.76*	0.70*	0.82**	1							
Exch.Ca	0.84**	0.90**	0.63tn	0.98**	0.92**	1						
Exch. Mg	0.97**	0.97**	0.58tn	0.92**	0.66tn	0.87**	1					
Exch. Na	0.93**	0.94**	0.57tn	0.98**	0.74*	0.94**	0.95**	1				
CEC	0.94**	0.96**	0.63tn	0.95**	0.76*	0.93**	0.99**	0.97**	1			
BS	0.87**	0.94**	0.64tn	0.98**	0.87**	0.98**	0.91**	0.97**	0.95**	1		
Height	0.51tn	0.73**	0.88**	0.69*	0.85**	0.78**	0.61tn	0.69*	0.69*	0.78*	1	
Stem Diameter	0.69*	0.87**	0.76*	0.78*	0.88**	0.89**	0.79*	0.76*	0.84**	0.84**	0.84**	1

Remarks : tn = not significant correlation at the 5% level; * significant correlation at the 1% level
** highly significant correlation at the 1% level

The vegetative growth of plants (plant height and stem diameter) is influenced by the high Nitrogen content (Garza-Alonso et al., 2019; Longnecker, 2021) as Nitrogen functions to increase leaf quantity and area, thereby affecting photosynthesis (Chang et al., 2020; Croft et al., 2017; Ren et al., 2018). Phosphorus plays a role in protein synthesis and cell division, promoting tissue development (Saleem et al., 2020; Zhang et al., 2023). Potassium is involved in photosynthesis (Rawat et al., 2022; Xie et al., 2021), enhancing growth and leaf area index. It also improves CO_2 assimilation and the translocation of photosynthetic products from leaves to other plant parts (Tombesi et al., 2019; Xu et al., 2020). The translocation of photosynthetic products is enhanced by an increase in ATP production, which is crucial for loading assimilates into the phloem (de Bang et al., 2021; Giaquinta, 1983). Plant growth is promoted when essential nutrients are sufficiently available in the soil, leading to improved physiological and metabolic processes (Niu et al., 2018; Rawat et al., 2019). Plants absorb nutrients dissolved in the soil for their growth (Gondek et al., 2020; Havlin, 2020; Kathpalia & Bhatla, 2018).

5. CONCLUSION

The addition of 0.2 kg of red mud and 3 kg of cow manure fertilizer can increase soil pH, the availability of soil macro-nutrients, and the growth of corn plants compared to the addition of red mud and cow manure fertilizer at lower doses. Therefore, it offers a pathway to promote sustainable and effective soil rejuvenation. For further research, field studies are essential to validate these findings and explore the long-term impacts on soil health and crop productivity.

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Declaration of Competing Interest

The authors declare that no competing financial or personal interests that may appear and influence the work reported in this paper.

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