AgriHealth
Journal of Agri-food, Nutrition and Public Health
ISSN 2722-0656 (Print) 2722-0648 (Online)
AgriHealth: Journal of Agri-food, Nutrition and Public Health. 6(1), 71-84, 2025
URL: https://jurnal.uns.ac.id/agrihealth/article/view/104807
DOI: http://dx.doi.org/10.20961/agrihealth.v6i1.104807

Effects of Red Mud and KCl Fertilizer Combination on Nutrient Availability and Growth of Maize (*Zea mays* L.) in Peatland Soils

Sulakhudin[1*] and Surachman[2]

[1]Department of Soil Science, Faculty of Agriculture, Universitas Tanjungpura, Pontianak, Indonesia; [2]Department of Agrotechnology, Faculty of Agriculture, Universitas Tanjungpura, Pontianak, Indonesia

Received: June 25, 2025; **Accepted**: July 7, 2025

Abstract

Tropical peatlands in West Kalimantan are severely constrained by extreme acidity (pH < 4.5), limiting maize productivity to 15 to 35% of genetic potential. Traditional peat burning exacerbates environmental degradation through CO_2 emissions and particulate matter release. This study evaluated red mud-KCl fertilizer combinations on soil nutrient availability and maize growth. A randomized complete block design examined five treatments with five replications (n = 25). Four treatment levels (R1 to R4) were applied with red mud doses (0.75 to 3.0 kg plot^{-1}) with KCl fertilizer (42.6 g) versus controls. Red mud, an alkaline bauxite waste (pH 10 to 12), maintained heavy metal concentrations below regulatory thresholds. Statistical analyses employed ANOVA ($\alpha = 0.05$) and Duncan's Multiple Range Test. Treatments significantly elevated soil pH from 4.41 (control) to 5.45 to 5.67, transforming strongly acidic to moderately acidic conditions. Exchangeable K increased from 2.02 to 4.40 cmol(+) kg^{-1}, representing a 118% improvement in K availability. Available P improved by 13.4%, enhancing nutrient uptake capacity. The optimal treatment (R4: 3.0 kg red mud + KCl) demonstrated superior maize performance with significantly greater plant height, stem diameter, and maize ear weight than controls. Treatment R4 achieved the most favorable soil chemical properties, including optimal cation exchange capacity and nutrient retention, creating ideal growing conditions that maximized maize genetic potential expression in previously unproductive acidic peatland soils. Results indicate substantial potential for sustainable peatland agriculture through red mud-KCl soil amendments. Future investigations should assess long-term environmental sustainability, socio-economic viability, and farmer adoption mechanisms for implementing this amelioration strategy in tropical peatland systems.

Keywords: amelioration; KCl fertilizer; maize cultivation; peatland; red mud

INTRODUCTION

The increasing global pressure on agricultural systems to enhance food production while maintaining environmental integrity has intensified scientific attention toward previously underutilized ecosystems, particularly tropical peatlands (Mishra et al., 2021). Carbon-rich peatlands have significant potential for agricultural expansion, but some of their chemical and physical properties make them less able to support optimal plant growth (Rodzkin et al., 2021). West Kalimantan's extensive peatland coverage—approximately 1.73 million hectares constituting 11.6% of the provincial territory (Nusantara et al., 2020), exemplifies this paradox of agricultural opportunity constrained by pedological limitations (Purwanto, 2018).

The cultivation of maize (*Zea mays* L.) in peatlands has so far only produced results

* **Corresponding author**: sulakhudin@faperta.untan.ac.id

Cite this as: Sulakhudin & Surachman. (2025). Effects of Red Mud and KCl Fertilizer Combination on Nutrient Availability and Growth of Maize (*Zea mays* L.) in Peatland Soils. *AgriHealth: Journal of Agri-food, Nutrition and Public Health*, *6*(1), 71-84. doi: http://dx.doi.org/10.20961/agrihealth.v6i1.104807

far below its genetic potential under optimal conditions, its productivity ranges from 1.2 to 2.8 tons $ha^{-1,}$ equivalent to 15 to 35% of its maximum productivity potential (Widiastuti et al., 2024). Low productivity is mainly caused by the high acidity level of tropical peat soil, which reaches a pH value of < 4.5 (Kunarso et al., 2022). This condition causes a series of limiting factors for plant growth, such as decreased availability of nutrients, increased concentrations of toxic compounds, and decreased activity of beneficial microbes (Agus et al., 2019).

Traditional farmer responses to these pedological constraints have predominantly involved peat burning practices, which, while temporarily ameliorating soil acidity through ash alkalinization (Arunrat et al., 2024), generate severe environmental and public health consequences (Hein et al., 2022). The combustion process releases substantial quantities of particulate matter ($PM_{2.5}$ and PM_{10}), contributing to respiratory health complications that disproportionately affect vulnerable populations (Eng et al., 2024). Epidemiological evidence indicates 40 to 60% increases in acute respiratory infection incidence during burning seasons (Uda et al., 2019).

The smoke caused by peatland burning, and its direct impact on human health, could also contribute to the release of vast amounts of CO_2, reaching 500 to 1,500 tons of CO_2-equivalent (Sasmito et al., 2025). This condition would eliminate peatlands' critical role as natural C storage and increase greenhouse gas emissions globally (Strack et al., 2022). The environmental impact of peatland burning encourages the creation of a peatland management approach with sustainable amelioration technology by utilizing materials that have not been optimally used, for example, waste from the mining industry, whose location is not too far from the peatland (Syahza et al., 2020).

Red mud was one of the mining industry wastes that has not been optimally utilized as an ameliorant, especially to improve several properties of peat soil (Juhari et al., 2024). It, the primary byproduct of alumina production through the Bayer process, is generated at approximately 2.5 million tonnes annually in West Kalimantan (Abdul et al., 2024). This highly alkaline material (pH 10 to 12) contains substantial quantities of Ca, Al, and Fe_2O_3, alongside agriculturally relevant macronutrients including P and K (Samal, 2021). Previous investigations have demonstrated red mud's capacity to neutralize peat acidity effectively (Sulakhudin et al., 2024), with application rates of 4 tons ha^{-1} elevating soil pH while enhancing N, P, and K availability (Surachman et al., 2024).

The presence of high Na content reduces the positive effect of increasing pH by adding red mud, which often contains more than 5% Na, so it can negatively impact soil and plants (Cai et al., 2023). Soil with high Na content disrupts water balance in plant cells, inhibits the process of photosynthesis, and causes ionic antagonism effects that will reduce the efficiency of K absorption by plant roots (Mostofa et al., 2022). Furthermore, maize plants that grow on soil with high Na content have chlorotic leaves, stunted growth, and decreased yields by 30 to 50% (Iqbal et al., 2020).

Red mud contains heavy metals including Al, As, and Ti (Xue et al., 2025). Chemical analysis reveals 10.25% aluminum oxide (Al_2O_3), 3.67% titanium dioxide (TiO_2) (Tanvar and Mishra, 2025), and As concentrations of 200 ppm (Lockwood et al., 2014), varying with bauxite ore origin. Despite potentially hazardous elements, concentrations in amended soils remain below regulatory thresholds. Contemporary research demonstrates that heavy metal fractions become stable through precipitation, adsorption, and ion exchange mechanisms, reducing bioavailability (Li et al., 2025). Comprehensive assessments confirm low leaching potential under typical conditions, maintaining acceptable concentrations for agricultural applications.

Mixing red mud with KCl fertilizer offers an approach that can effectively reduce the adverse effects of Na elements through ionic competition because K and Na ions have one positive charge (Chao et al., 2022). High K levels can suppress the absorption of Na elements in the root membrane, so less Na enters the plant organs (Joshi et al., 2022). This approach can not only overcome ion imbalances due to red mud applications but also maintain pH buffer properties and increase the availability of nutrients in peat soil (Ding et al., 2023).

Despite promising individual component results, the interactive effects of combined red mud and KCl application on peat soil biogeochemistry and maize performance remain insufficiently characterized. Previous research has predominantly examined red mud applications in isolation or combined with conventional organic amendments (Reddy et al., 2020), overlooking the complex biogeochemical interactions within peat soil matrices. The knowledge gap regarding the application of red mud mixed with KCl is a fundamental limitation in the management of peatlands with sustainable amelioration technology.

Literature demonstrates insufficient understanding of red mud-KCl synergistic effects on peat soil amelioration. This gap analysis reveals critical knowledge deficits regarding optimal application protocols, biogeochemical interactions, and long-term C stability impacts. Investigating integrated amendment systems' scalability and economic viability in tropical peatland agriculture remains essential for sustainable management strategies. This study comprehensively examines the application of a mixture of red mud and KCl fertilizer with a focus on peatland maize cultivation in terms of modifying soil chemical properties, including pH dynamics, macronutrient availability patterns, and maize plant growth. This research, in addition to having implications for sustainable peatland management, also has an impact on protecting public health by reducing peatland burning, encouraging secular economic development through the utilization of bauxite mining industry waste, and mitigating climate change by maintaining C stocks in peatlands.

MATERIALS AND METHOD

Location and soil characteristics

A field experiment was conducted on 1.5 m × 3 m plots in hemic peatland at Punggur Kecil Village, Kubu Raya Regency, West Kalimantan (109°29'22.9" E, 0°16'59.6" S) from March to September 2024. The experimental site featured moderately decomposed peat soil with variable cation concentrations and critically low base saturation levels that constrained plant development (Table 1).

Experimental design

A randomized complete block design was implemented with five treatments and five replications (n = 25). Treatments included: control (R0), red mud at 3 kg plot^{-1} (R1), red mud application at 3 kg plot^{-1} + KCl fertilizer at 10.6 g (R2), red mud application at 3 kg plot^{-1} + KCl fertilizer at 21.1 g (R3), red mud application at 3 kg plot^{-1} + KCl fertilizer at 42.6 g (R4). Red mud dosage determination was conducted through preliminary experimentation, whereby peat soil was systematically amended with red mud to achieve the optimal soil pH of 5.5 for crop production. Achievement of this target pH necessitated a 1:70 mass ratio of red mud to peat soil. KCl fertilizer rates were computed based on the exchangeable Na concentration inherent in red mud. Subsequently, equivalence was established for exchangeable K, considering their equivalent monovalent cationic properties, then converted to determine requisite KCl application rates.

Red mud from Indonesia Chemical Alumina, Ltd. (Tayan Hilir, West Kalimantan) exhibited pH 10.87, 0.95% organic C, and base cations of 0.11, 11.37, 0.06, and 68.76 cmol(+) kg^{-1} for K, Ca, Mg, and Na, respectively. The KCl fertilizer used contains 60% K_2O. Treatments were thoroughly incorporated into soil, with basal fertilization at 230-144-180 kg ha^{-1} N-P_2O_5-K_2O (Juhari et al., 2024).

Table 1. Peat soil analysis results at the experimental site

Parameter	Value	Criteria
pH (H_2O)	3.08	Extremely acidic
Organic C (%)	55.74	Very high
Total N (%)	1.68	Very high
Available P (ppm)	71.47	Very high
Exchangeable Ca (me 100 g^{-1})	4.21	Low
Exchangeable Mg (me 100 g^{-1})	4.20	High
Exchangeable K (me 100 g^{-1})	0.98	High
Exchangeable Na (me 100 g^{-1})	0.57	Moderate
Cation exchange capacity (me 100 g^{-1})	115.55	Very high
Base saturation (%)	8.51	Very low

Note: Classification criteria based on Eviati et al. (2023)

Parameter observation

Soil samples were collected after 28-day incubation and analyzed at Universitas Tanjungpura's Soil Chemistry Laboratory. Soil pH was determined using a pH meter in a 1:5 soil-to-water ratio suspension following the standard procedure described by Singh (2024). Soil salinity and electrical conductivity (EC) were measured in saturated soil paste extracts according to the method outlined by Behera (2022). Total N content was determined using the Kjeldahl digestion method as described by Kumar (2022). Available P was extracted using the Bray-1 method (Matcham et al., 2023), which involves extraction with 0.03 M NH_4F and 0.025 M HCl solution. Exchangeable P and Na were extracted using 1 M NH_4OAc at pH 7.0 following the procedure described by Eviati et al. (2023). The extracted cations were analyzed using atomic absorption spectrophotometry (AAS). Plant height and stem diameter were monitored weekly throughout the late vegetative stage. Plant height was measured from the soil surface to the highest growing point, while stem diameter was measured 5 cm above the soil surface using digital calipers (Bernhard and Below, 2020). Maize yield parameters were evaluated by determining ear weight with husk (EWH) and ear weight without husk (EWOH).

Analysis data

Data underwent Shapiro-Wilk and Levene's tests for normality and variance homogeneity, with transformation applied when necessary. Analysis of Variance (ANOVA) (α = 0.05) determined treatment effects, followed by Duncan's Multiple Range Test (DMRT) for mean separation when significant differences occurred (Glaz and Yeater, 2020).

RESULTS AND DISCUSSION

Effects of red mud and KCl mixture on selected chemical properties of peatland soils

The application of red mud and KCl demonstrated significant efficacy in ameliorating peat soil acidity, elevating pH from 4.41 (control) to 5.45 to 5.67 across treatments (Table 2). This remarkable pH elevation represents a fundamental shift from strongly acidic to moderately acidic conditions, aligning with the inherent alkaline properties of red mud (Archambo and Kawatra, 2021), which typically maintains pH values between 10 and 13 (Ilahi et al., 2024). This pH enhancement mechanism operates through the neutralization capacity of red mud's alkaline constituents, including CaO (52.48%), Na_2O (41.9%), MgO (0.07%), and K_2O (0.03%) (Santini et al., 2015), which facilitate cation exchange processes whereby basic cations displace H^+ ions in the peat soil sorption complex while releasing OH^- ions into the soil solution (Sharma et al., 2025). In line with Maswar et al. (2021), the provision of ameliorants rich in base cations can increase the pH of peat soil from 3.72 to 6.93. However, the treated soils have not yet achieved the optimal pH range of 5.0 to 6.0, which is required for most peat crops (Zhou, 2024). These improvements represent substantial progress toward creating more favorable growing conditions in naturally acidic peat environments (Harmaji et al., 2024), which typically exhibit low pH due to organic acid accumulation from partially decomposed plant materials under anaerobic conditions (Nurzakiah et al., 2021).

The progressive increase in pH values from R1 (5.45) to R4 (5.67) suggests a dose-dependent response, although statistical analysis revealed no significant differences among the red mud treatments. This indicates that even the lowest application rate (R1) was sufficient to achieve near-maximum pH buffering capacity within the experimental timeframe. The enhanced pH conditions facilitate several critical soil processes, including improved nutrient solubility, enhanced microbial activity, and reduced aluminum toxicity, collectively contributing to improved soil fertility (Gondal et al., 2021).

Table 2 also shows that EC measurements gradually increased from 2.99 mS cm^{-1} in the control to 3.74 mS cm^{-1} in the highest red mud treatment (R4). However, these differences were not statistically significant. This modest elevation in EC reflects the introduction of soluble salts inherent in red mud composition, particularly Na compounds that contribute to the material's high alkalinity (Jiang et al., 2023). The corresponding salinity levels remained consistently low across all treatments (0.08 to 0.09 ppt), indicating that the red mud applications did not induce problematic salt accumulation that could potentially harm plant growth or soil biological activity (Wang and Liu, 2021).

These findings are particularly reassuring from an agricultural sustainability perspective, as excessive salinity can severely compromise plant nutrient uptake. Despite significant pH

Table 2. Chemical properties of peat soil under various doses of red mud and KCl

Treatment	pH	Salinity (ppt)	EC mS (cm^{-1})	Total N (%)	Available P (ppm)	Exchangeable K	Exchangeable Na
						(cmol(+) kg^{-1})	
R0	4.41±0.05^{b}	0.08±0.01^{a}	2.99±0.54^{a}	3.01±0.09^{a}	85.50±1.58^{a}	2.02±0.71^{b}	1.20±0.13^{b}
R1	5.45±0.15^{a}	0.09±0.01^{a}	3.04±0.31^{a}	2.83±0.07^{a}	86.48±3.52^{a}	2.19±0.78^{a}	9.24±0.82^{a}
R2	5.52±0.15^{a}	0.09±0.01^{a}	3.07±0.28^{a}	3.07±0.08^{a}	87.92±1.35^{a}	2.79±0.05^{a}	9.83±1.11^{a}
R3	5.64±0.20^{a}	0.09±0.01^{a}	3.30±0.52^{a}	3.00±0.16^{a}	90.82±2.04^{a}	3.23±0.87^{a}	9.86±2.52^{a}
R4	5.67±0.09^{a}	0.09±0.01^{a}	3.74±0.55^{a}	3.33±0.50^{a}	96.97±10.80^{a}	4.40±0.82^{a}	10.15±0.82^{a}

Note: EC = Electrical conductivity. Values mean±standard error, SE (n = 5), values followed by the same letter within the same column are not significantly different according to DMRT at 5% significance level

improvements, the maintenance of low salinity levels suggests that the red mud used in this study possessed relatively low concentrations of highly soluble salts, making it suitable for soil amendment applications (Taneez and Hurel, 2019). The slight increase in EC may be beneficial, as it indicates enhanced ion exchange capacity and improved nutrient retention potential within the amended soil matrix (Lwin et al., 2018).

Total N content remained relatively stable across treatments (2.83 to 3.33%) with no statistically significant differences (Table 2). This indicates that red mud amendment neither contributes substantial N quantities nor significantly alters N mineralization processes within the experimental timeframe. The consistent N levels around 3% reflect the peat soil's inherently high organic matter content, which serves as a substantial N reservoir, and suggest that organic N pools within the peat matrix remained intact despite significant pH changes (Arsenault et al., 2024). This stability is noteworthy because rapid pH modifications sometimes trigger accelerated organic matter decomposition, potentially causing N losses through volatilization or leaching. The maintained N content provides a solid foundation for long-term soil fertility, as organic N pools will gradually mineralize to supply plant-available forms as soil conditions improve. In contrast, the slightly elevated N content in R4 (3.33%), though not statistically significant, may indicate enhanced N retention capacity associated with improved soil pH and cation exchange properties (Gao et al., 2022).

Available P concentrations demonstrated a consistent upward trend across red mud treatments, increasing from 85.50 ppm in the control to 96.97 ppm in R4 (Table 1), representing a 13.4% improvement in P availability. While these differences were not statistically significant at the 5% level, the consistent pattern suggests a genuine enhancement in P mobilization associated with pH improvement (Zhang et al., 2021). This response aligns with well-established principles of soil chemistry, where P availability is enhanced above a soil pH of 6.0, with low pH conditions generally resulting in reduced P availability (Luo et al., 2021).

Red mud application demonstrated remarkable enhancement in exchangeable K concentrations (Table 2), with levels increasing from 2.02

cmol(+) kg^{-1} in control treatments to 4.40 cmol(+) kg^{-1} in R4, effectively doubling the available K reservoir. This substantial improvement is particularly beneficial for peat soils, which suffer from K deficiency due to minimal mineral weathering processes and their predominantly organic matrix composition. The enhanced K availability stems from dual mechanisms: direct mineral contribution from K-bearing compounds within red mud and improved K retention facilitated by elevated pH increases (Choo et al., 2022). Since K availability optimizes above pH 6.0, with acidic conditions severely limiting soil K supply to vegetation, the pH amelioration achieved through red mud treatment positions the soil environment closer to these favorable conditions, consequently maximizing both K retention efficiency and plant accessibility (Zhou et al., 2024).

Sodium accumulation in soil occurs through gradual release mechanisms from red mud within the peat matrix (Tong et al., 2025). Red mud amendments yielded substantial transformations in exchangeable cation dynamics, with Na concentrations escalating dramatically from 1.20 cmol(+) kg^{-1} in controls to 9.24 to 10.15 cmol(+) kg^{-1} across treatments (Table 2), reflecting red mud's inherent Na content predominantly manifested as NaOH and $AlNa_{12}SiO_5$ (sodium aluminosilicates) (Lan et al., 2022). Concurrently, exchangeable K experienced remarkable augmentation from 2.02 to 4.40 cmol(+) kg^{-1} in R4, effectively doubling available reserves. The substantial elevation of Na concentrations in peat soils warrants careful consideration due to potential adverse implications for plant development. McCarter et al. (2018) demonstrate that Na increases exceeding 2.5 cmol(+) kg^{-1} in peat soils can disrupt the uptake of essential nutrients, particularly K and Ca, through ionic antagonistic mechanisms. Consequently, red mud utilization as a soil ameliorant requires precise dosage optimization to mitigate negative consequences associated with Na enhancement.

The chemical transformation of peat soil properties following red mud and KCl amendments, particularly pH elevation from strongly acidic conditions (4.41) to moderately acidic levels (5.45 to 5.67), exchangeable K enhancement from 2.02 to 4.40 cmol(+) kg^{-1}, alongside modifications in Na and other nutrient concentrations, exerted significant influence on maize growth performance. These soil chemical improvements established more favorable conditions for root system development and nutrient acquisition by maize plants (Reeza et al., 2023).

Effects of red mud and KCl application on maize growth

Maize cultivation in peatland environments requires optimal nutrient availability and appropriate soil acidity levels for successful plant development, with growth parameters including plant height and stem diameter serving as indicators of plant responses to enhanced soil conditions through red mud and KCl applications. Plant height monitoring throughout 6 weeks revealed initially uniform growth across all treatments during weeks I to II, followed by significant differentiation from week III onward, where treatment R4 (red mud 3 kg $plot^{-1}$ + KCl 42.6 g) consistently exhibited superior development compared to treatments R2 and R3, while R0 demonstrated minimal growth (Figure 1). This enhanced performance directly correlates with improved peat soil chemical properties, particularly pH elevation and nutrient availability from red mud application, supporting Juhari et al. (2024), which demonstrates how peat soil amelioration using polyvalent cation-containing materials enhances nutrient uptake efficiency and promotes optimal vegetative growth in maize cultivation systems.

Growth rate analysis revealed accelerated plant height increases during weeks III to VI, with treatment R4 achieving maximum height at observation termination. This significant enhancement can be attributed to improved macronutrient availability mechanisms, particularly the crucial role of K in cell elongation and protein synthesis for vegetative development (Sardans and Peñuelas, 2021). These findings corroborate research by Elsonbaty et al. (2025) demonstrating that alkaline ameliorant-K fertilizer combinations optimize nutrient uptake and enhance photosynthetic efficiency, ultimately supporting plant height development. The differential growth responses observed among treatments indicate synergistic effects between red mud and KCl in improving peat soil rhizosphere conditions. The difference in the growth of maize plants in the control and maize plants in the treatment of red mud and KCl fertilizer can be seen in Figure 2.

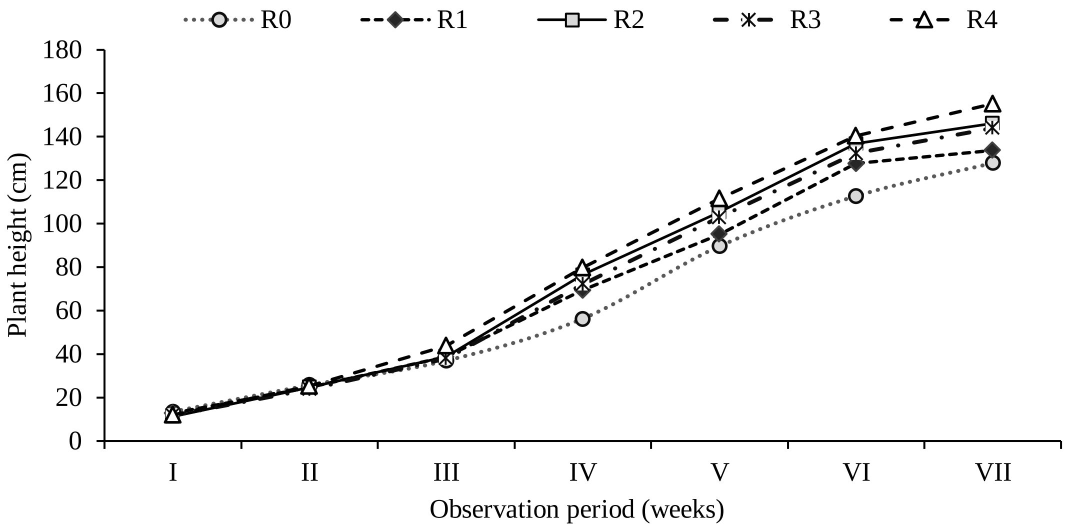

Figure 1. Effects of red mud and KCl combinations on maize plant height in peatland

Figure 2. Growth of maize plants in the treatment R0 (a) and R4 administration of 3 kg of red mud and 42.6 g of KCl fertilizer per plot (b)

Optimal maize height development under red mud and KCl treatments correlates closely with stem diameter progression as a critical vegetative growth parameter. Stem diameter represents structural strength indicators and plant capacity for water and nutrient translocation from roots to aerial portions. According to Xue et al. (2020), positive correlations exist between plant height development and stem diameter progression, where plants achieving optimal height typically exhibit proportional stem diameter to support vertical growth architecture.

Stem diameter observations (Figure 3) demonstrated growth patterns paralleling plant height parameters, revealing significant differences between control treatments (R0) and red mud-KCl combinations (R1 to R4). Initial growth phases (weeks I to II) exhibited uniform stem diameter development across treatments; however, substantial increases occurred from week III through V, particularly in treatment R4, displaying maximum stem diameter enhancement. According to Sinaga et al. (2020), optimal stem diameter improvement relates to enhanced physical and chemical conditions in peat soils following ameliorant and fertilizer applications. These soil property improvements support vascular tissue and stem cell development through increased essential nutrient availability, especially the vital role of K in cell division and enlargement processes.

Stem diameter growth trend analysis revealed accelerated development rates during weeks III to V, with treatment R4 (red mud 3 kg plot^{-1} + KCl

42.6 g) consistently demonstrating superior performance, followed by treatments R2 and R3. This indicates synergistic effects between red mud and KCl in enhancing soil capacity for nutrient provision, supporting stem diameter development. Differential treatment responses demonstrate that red mud dosage of 3 kg $plot^{-1}$ combined with KCl (R4) represents the optimal combination for promoting maize stem diameter development in peat soils. However, consideration must be given to ameliorant dosage increases respecting plant tolerance limits to soil chemical characteristic changes, avoiding adverse effects on plant growth (Di Carlo et al., 2019).

Red mud utilization for peat soil amelioration provides dual environmental benefits by converting industrial waste into valuable agricultural resources while addressing productivity constraints. This approach demonstrates superior efficacy over conventional lime applications, optimizing pH levels and enhancing nutrient bioavailability and cation exchange capacity in acidic, nutrient-deficient peat systems. The comprehensive soil chemical improvements establish red mud as a promising foundation for sustainable agricultural intensification, effectively transforming marginal peat soils into productive cultivation systems. These findings highlight potential synergies between industrial waste management and agricultural enhancement, though optimization of application protocols and long-term sustainability assessments across diverse cropping systems requires further investigation.

The combined application of red mud and KCl treatments significantly influenced maize ear weight parameters (Figure 4). Treatment R4 achieved the highest ear weights with husk (1,552.0 g) and without husk (926.40 g), substantially exceeding control values of 842.60 and 496.20 g, respectively. The EWOH to EWH ratio of 59.7% in R4 indicated superior grain filling efficiency, demonstrating that 3 kg $plot^{-1}$ red mud combined with 42.6 g KCl effectively optimized ear development. These results support previous findings (Rehman and Ikram, 2020) that optimal nutrient availability, particularly K, facilitates photosynthate translocation to reproductive organs, enhancing grain formation processes.

Enhanced ear weights correlated with improved root development and nutrient uptake capacity, particularly for P and K, which are essential in grain filling. The amelioration of peat soil properties through red mud application and KCl-derived K availability created favorable rhizosphere conditions for ear development. While consistent improvements from R0 to R4 were observed for both parameters, treatments R1 to R3 showed modest variations, suggesting that higher red mud dosages (up to 3 kg $plot^{-1}$) combined with KCl positively influence maize productivity on peat soils. However, economic viability must be considered when determining optimal application rates, as yield increases between R3 and R4 warrant cost-benefit analysis for practical implementation.

While red mud demonstrates considerable agronomic potential, its agricultural implementation demands rigorous evaluation of inherent environmental hazards. The predominant toxicological concerns arise from red mud's

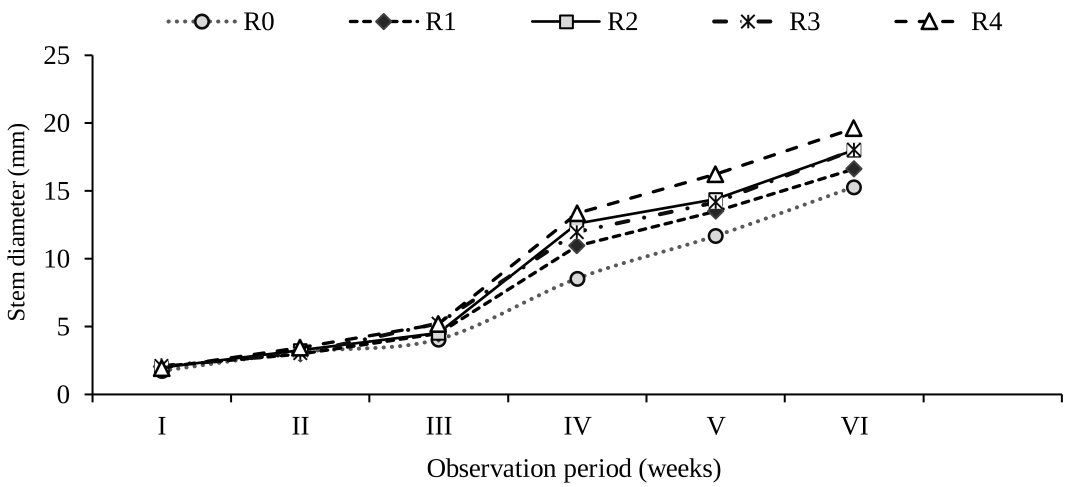

Figure 3. Effects of red mud and KCl combinations on maize stem diameter in peatland

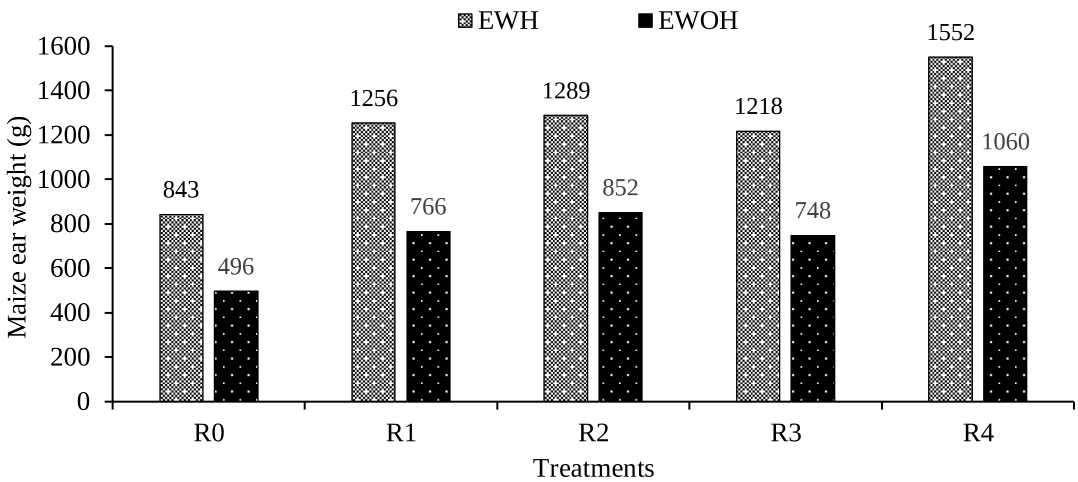

Figure 4. Effects of red mud and KCl combination on maize EWH and EWOH in peat soil

extreme alkalinity (pH 10 to 13) and excessive Na concentrations, which may provoke osmotic stress responses and substantially diminish crop productivity (Anam et al., 2019). The elevated Na_2O constituents possess the capacity to infiltrate adjacent soil matrices through leaching mechanisms, thereby precipitating soil salinization and groundwater contamination (Zhou et al., 2024), presenting acute challenges within the particularly susceptible peat ecosystem framework. Red mud contains an array of potentially toxic heavy metals encompassing As, Cr, Hg, Cd, and Pb (Vuković et al., 2024). Paradoxically, red mud amendments demonstrate the capacity for mitigating potentially toxic element (PTE) bioavailability in previously contaminated soils (Hua et al., 2017).

Nevertheless, these heavy metals retain the potential to compromise cellular structure and disrupt fundamental metabolic pathways. At the same time, their recalcitrant nature may facilitate chronic accumulation phenomena that adversely impact crop quality and long-term agricultural productivity (Xu et al., 2024). Consequently, systematic monitoring protocols for metallic contaminants in soil matrices and harvested agricultural products remain imperative to safeguard food security parameters and ensure environmental sustainability objectives (Charan and Bhattacharyya, 2023).

CONCLUSIONS

The synergistic application of red mud and KCl fertilizer successfully ameliorated strongly acidic tropical peatland soils, elevating pH from 4.41 to 5.67 while enhancing exchangeable K and P bioavailability. Optimal maize performance was achieved under the R4 treatment (3 kg red mud + 42.6 g KCl), demonstrating the efficacy of this soil amendment strategy. However, potential Na accumulation and trace metal concerns require comprehensive long-term assessments of soil health, food safety, and environmental impacts. Future research should prioritize techno-economic feasibility analyses and stakeholder engagement for sustainable technology adoption in peatland agriculture.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to the Rector of Universitas Tanjungpura and the Dean of the Faculty of Agriculture, Universitas Tanjungpura, for their continuous support and encouragement throughout this research project. Authors are deeply grateful for the institutional backing that made this study possible. This research was financially supported by the DIPA (*Daftar Isian Pelaksanaan Anggaran*) program under contract number 2560/UN22.3/PT.01.03/2024 dated April 1, 2024. The authors acknowledge that this funding support is essential for completing this work.

REFERENCES

Abdul, F., Isworo, G., Mahaputra, R., & Pintowantoro, S. (2024). Possible strategies for red mud neutralization and dealkalization from the alumina production industry: A review for Indonesia. *International Journal of Environmental Science and Technology*, *22*(6), 5159–5178. https://doi.org/10.1007/s13762-024-06122-5

Agus, C., Ilfana, Z. R., Azmi, F. F., Rachmanadi, D., Widiyatno, Wulandari, D., ..., & Lestari, T. (2019). The effect of tropical peat land-use changes on plant diversity and soil properties. *International Journal of Environmental Science and Technology*, *17*(3), 1703–1712. https://doi.org/10.1007/s13762-019-02579-x

Anam, G. B., Reddy, M. S., & Ahn, Y.-H. (2019). Characterization of *Trichoderma asperellum* RM-28 for its sodic/saline-alkali tolerance and plant growth promoting activities to alleviate toxicity of red mud. *Science of the Total Environment*, *662*, 462–469. https://doi.org/10.1016/j.scitotenv.2019.01.279

Archambo, M., & Kawatra, S. K. (2021). Red mud: Fundamentals and new avenues for utilization. *Mineral Processing and Extractive Metallurgy Review*, *42*(7), 427–450. https://doi.org/10.1080/08827508.2020.1781109

Arsenault, J., Talbot, J., Moore, T. R., Knorr, K.-H., Teickner, H., & Lapierre, J.-F. (2024). Patterns and drivers of organic matter decomposition in peatland open-water pools. *Biogeosciences*, *21*(15), 3491–3507. https://doi.org/10.5194/bg-21-3491-2024

Arunrat, N., Kongsurakan, P., Solomon, L. W., & Sereenonchai, S. (2024). Fire impacts on soil properties and implications for sustainability in rotational shifting cultivation: A review. *Agriculture*, *14*(9), 1660. https://doi.org/10.3390/agriculture14091660

Behera, R. D. (2022). *Soil and plant analysis* (1st ed). New Delhi, India: New India Publishing Agency. Retrieved from https://books.google.co.id/books/about/Soil_And_Plant_Analysis.html?id=MieiEAAAQBAJ&redir_esc=y

Bernhard, B. J., & Below, F. E. (2020). Plant population and row spacing effects on corn: Plant growth, phenology, and grain yield. *Agronomy Journal*, *112*(4), 2456–2465. https://doi.org/10.1002/agj2.20245

Cai, T., Pan, R., & Yang, M. (2023). Study on the effect of structural sodium dissolution on the physical properties of red mud treated by sulfuric acid. *Minerals Engineering*, *204*, 108424. https://doi.org/10.1016/j.mineng.2023.108424

Chao, X., Zhang, T., Lyu, G., Liang, Z., & Chen, Y. (2022). Sustainable application of sodium removal from red mud: Cleaner production of silicon-potassium compound fertilizer. *Journal of Cleaner Production*, *352*, 131601. https://doi.org/10.1016/j.jclepro.2022.131601

Charan, K., & Bhattacharyya, P. (2023). Vermicomposted red mud-An up-and-coming approach towards soil fertility and crop quality. *Journal of Crop and Weed*, *19*(2), 36–51. https://doi.org/10.22271/09746315.2023.v19.i2.1701

Choo, L. N. L. K., Ahmed, O. H., Razak, N. A., & Sekot, S. (2022). Improving nitrogen availability and *Ananas comosus* L. Merr var. Moris productivity in a tropical peat soil using clinoptilolite zeolite. *Agronomy*, *12*(11), 2750. https://doi.org/10.3390/agronomy12112750

Di Carlo, E., Chen, C. R., Haynes, R. J., Phillips, I. R., & Courtney, R. (2019). Soil quality and vegetation performance indicators for sustainable rehabilitation of bauxite residue disposal areas: A review. *Soil Research*, *57*(5), 419. https://doi.org/10.1071/SR18348

Ding, S., Zhang, T., Fan, B., Fan, B., Yin, J., Chen, S., ..., & Chen, Q. (2023). Enhanced phosphorus fixation in red mud-amended acidic soil subjected to periodic flooding-drying and straw incorporation. *Environmental Research*, *229*, 115960. https://doi.org/10.1016/j.envres.2023.115960

Elsonbaty, A., Abdelaziz, M., Abd El-Hady, A. S., & El-Sherpiny, M. A. (2025). Optimizing maize productivity as a strategic crop under alkaline soil conditions through organic fertilization and nanoparticle-based potassium sources. *Egyptian Journal of Soil Science*, *65*(1), 91–107. https://doi.org/10.21608/ejss.2024.323304.1865

Eng, H. E., Teoh, C. S., Ismail, F., Razak, A. S. A., & Sulaiman, S. (2024). Elemental characteristics of particulate matter (PM_{10} and $PM_{2.5}$) from peat swamp area in Kuala Pahang. *Construction*, *4*(2), 222–228. https://doi.org/10.15282/construction.v4i2.10670

Eviati, Sulaeman, Herawaty, L., Anggria, L., Usman, Tantika, H. E., Prihatini, R., &

Wuningrum, P. (2023). *Petunjuk teknis edisi 3: Analisis kimia tanah, tanaman, air, dan pupuk*. Bogor, Indonesia: Soil and Fertilizer Instrument Standards Testing Center. Retrieved from https://tanahpupuk.bsip.pertanian.go.id/storage/assets/uploads/publikasi/Ho07w2htwf9OzGNVgMnfb1rsJrfxzYAjN687bbNC.pdf

Gao, S., Song, Y., Song, C., Wang, X., Gong, C., Ma, X., ..., & Du, Y. (2022). Long-term nitrogen addition alters peatland plant community structure and nutrient resorption efficiency. *Science of The Total Environment*, *844*, 157176. https://doi.org/10.1016/j.scitotenv.2022.157176

Glaz, B., & Yeater, K. M. (2020). *Applied statistics in agricultural, biological, and environmental sciences*. New York, United States: John Wiley & Sons. Retrieved from https://scholar.google.co.id/scholar?cites=9686142478723001530&as_sdt=2005&sciodt=0,5&hl=id

Gondal, A. H., Hussain, I., Ijaz, A. B., Zafar, A., Ch, B. I., Zafar, H., ..., & Usama, M. (2021). Influence of soil pH and microbes on mineral solubility and plant nutrition: A review. *International Journal of Agriculture and Biological Sciences*, *5*(1), 71–81. http://dx.doi.org/10.5281/zenodo.4625364

Harmaji, A., Jafari, R., & Simard, G. (2024). Valorization of residue from aluminum industries: A review. *Materials*, *17*(21), 5152. https://doi.org/10.3390/ma17215152

Hein, L., Spadaro, J. V., Ostro, B., Hammer, M., Sumarga, E., Salmayenti, R., ..., & Castañeda, J. P. (2022). The health impacts of Indonesian peatland fires. *Environmental Health, 21*(1), 62. https://doi.org/10.1186/s12940-022-00872-w

Hua, Y., Heal, K. V., & Friesl-Hanl, W. (2017). The use of red mud as an immobiliser for metal/metalloid-contaminated soil: A review. *Journal of Hazardous Materials, 325,* 17–30. https://doi.org/10.1016/j.jhazmat.2016.11.073

Ilahi, K., Debbarma, S., Mathew, G., & Inyang, H. I. (2024). Carbon capture and mineralisation using red mud: A systematic review of its principles and applications. *Journal of Cleaner Production*, *473*, 143458. https://doi.org/10.1016/j.jclepro.2024.143458

Iqbal, S., Hussain, S., Qayyaum, M. A., & Ashraf, M. (2020). The response of maize physiology under salinity stress and its coping strategies. *Plant stress physiology*. IntechOpen. https://doi.org/10.5772/intechopen.92213

Jiang, X., Zhang, X., Cheng, G., & Liu, J. (2023). Assessing the potential of red mud and dehydrated mineral mud mixtures as soil matrix for revegetation. *Journal of Environmental Management*, *344*, 118393. https://doi.org/10.1016/j.jenvman.2023.118393

Joshi, S., Nath, J., Singh, A. K., Pareek, A., & Joshi, R. (2022). Ion transporters and their regulatory signal transduction mechanisms for salinity tolerance in plants. *Physiologia Plantarum*, *174*(3), e13702. https://doi.org/10.1111/ppl.13702

Juhari, J., Iskandar, I., & Santosa, D. A. (2024). Utilization of red mud and biofertilizer for peat quality improvement and its effect on the growth and production of hybrid corn. *Agrikultura*, *35*(3), 573–585. https://doi.org/10.24198/agrikultura.v35i3.59075

Kumar, H. (2022). *Advanced techniques of analytical chemistry: Volume 1*. Singapore: Bentham Science Publishers. Retrieved from https://books.google.co.id/books?hl=id&lr=&id=nxJkEAAAQBAJ&oi=fnd&pg=PP1&dq=Advanced+Techniques+of+Analytical+Chemistry:+Volume+1&ots=QwS7NxWuYk&sig=3obGV-8n5Z0HnkfpEAqSefppWm8&redir_esc=y#v=onepage&q=Advanced%20Techniques%20of%20Analytical%20Chemistry%3A%20Volume%201&f=false

Kunarso, A., Bonner, M. T. L., Blanch, E. W., & Grover, S. (2022). Differences in tropical peat soil physical and chemical properties under different land uses: A systematic review and meta-analysis. *Journal of Soil Science and Plant Nutrition, 22*(4), 4063–4083. https://doi.org/10.1007/s42729-022-01008-2

Lan, X., Gao, J., Qu, X., & Guo, Z. (2022). An environmental-friendly method for recovery of soluble sodium and harmless utilization of red mud: Solidification, separation, and mechanism. *Resources, Conservation and Recycling*, *186*, 106543. https://doi.org/10.1016/j.resconrec.2022.106543

Li, K., Lu, X., Jiang, C., Wang, D., Zhu, J., Xu, M., ..., & Cheng, X. (2025). Evaluation of leaching characteristics of heavy metal ions from red mud–graphite tailings. *Toxics*, *13*(3), 211. https://doi.org/10.3390/toxics13030211

Lockwood, C. L., Mortimer, R. J., Stewart, D. I., Mayes, W. M., Peacock, C. L., Polya, D. A., ..., & Burke, I. T. (2014). Mobilisation of arsenic from bauxite residue (red mud) affected soils: Effect of pH and redox conditions. *Applied Geochemistry*, *51*, 268–277. https://doi.org/10.1016/j.apgeochem.2014.10.009

Luo, L., Ye, H., Zhang, D., Gu, J.-D., & Deng, O. (2021). The dynamics of phosphorus fractions and the factors driving phosphorus cycle in Zoige Plateau peatland soil. *Chemosphere*, *278*, 130501. https://doi.org/10.1016/j.chemosphere.2021.130501

Lwin, C. S., Seo, B.-H., Kim, H.-U., Owens, G., & Kim, K.-R. (2018). Application of soil amendments to contaminated soils for heavy metal immobilization and improved soil quality—A critical review. *Soil Science and Plant Nutrition*, *64*(2), 156–167. https://doi.org/10.1080/00380768.2018.1440938

Maswar, Firmansyah, A., Haryati, U., & Irawan. (2021). The effect of ameliorant on peat soil properties and shallots productivity in peatlands. *IOP Conference Series: Earth and Environmental Science*, *648*(1), 012057. https://doi.org/10.1088/1755-1315/648/1/012057

Matcham, E. G., Ruark, M. D., Stoltenberg, D. E., & Conley, S. P. (2023). Comparison of Bray-1 and Mehlich-3 extraction of P and K in Wisconsin silt loam soils. *Soil Science Society of America Journal*, *87*(4), 999–1002. https://doi.org/10.1002/saj2.20557

McCarter, C. P., Weber, T. K., & Price, J. S. (2018). Competitive transport processes of chloride, sodium, potassium, and ammonium in fen peat. *Journal of Contaminant Hydrology*, *217*, 17–31. https://doi.org/10.1016/j.jconhyd.2018.08.004

Mishra, S., Page, S. E., Cobb, A. R., Lee, J. S. H., Jovani-Sancho, A. J., Sjögersten, S., ..., & Wardle, D. A. (2021). Degradation of Southeast Asian tropical peatlands and integrated strategies for their better management and restoration. *Journal of Applied Ecology*, *58*(7), 1370–1387. https://doi.org/10.1111/1365-2664.13905

Mostofa, M. G., Rahman, M. M., Ghosh, T. K., Kabir, A. H., Abdelrahman, M., Khan, M. A. R., ..., & Tran, L. S. P. (2022). Potassium in plant physiological adaptation to abiotic stresses. *Plant Physiology and Biochemistry*, *186*, 279–289. https://doi.org/10.1016/j.plaphy.2022.07.011

Nurzakiah, S., Sutandi, A., Djajakirana, G., Sudadi, U., & Sabiham, S. (2021). The contribution of organic acid on heterotrophic CO_2 flux from tropical peat: A trenching study. *Journal of Degraded and Mining Lands Management*, *9*(1), 3035. https://doi.org/10.15243/jdmlm.2021.091.3035

Nusantara, R. W., Sudarmadji, S., Djohan, T. S., & Haryono, E. (2020). Impact of land-use change on soil carbon dynamics in tropical peatland, West Kalimantan-Indonesia. *Indonesian Journal of Geography*, *52*(1), 61–68. https://doi.org/10.22146/ijg.48451

Purwanto, E. A. (2018). Coping with policy paradoxes and actor interests in peatland and oil palm management in Indonesia. *Bisnis & Birokrasi Journal*, *25*(3), 2. Retrieved from https://scholarhub.ui.ac.id/jbb/vol25/iss3/2/

Reddy, P. S., Reddy, N. G., Serjun, V. Z., Mohanty, B., Das, S. K., Reddy, K. R., & Rao, B. H. (2020). Properties and assessment of applications of red mud (bauxite residue): Current status and research needs. *Waste and Biomass Valorization*, *12*(3), 1185–1217. https://doi.org/10.1007/s12649-020-01089-z

Reeza, A. A., Baharuddin, M. A. F., Ahmed, O. H., & Masuri, M. A. (2023). Nutrient uptake in different maize varieties (*Zea mays* L.) planted in tropical peat materials. *Pertanika Journal of Tropical Agricultural Science*, *46*(4), 1221–1232. https://doi.org/10.47836/pjtas.46.4.09

Rehman, A. P. D. H. U., & Ikram, M. (2020). Allometric effect of K_2O on morpho-physiological stages of maize crop. *Cereal*

Grain; Production and Improvement, pp. 21–46. Retrieved from https://iksadyayinevi.com/wp-content/uploads/2020/12/CEREAL-GRAIN-PRODUCTIONS-AND-IMPROVEMENT.pdf#page=28

Rodzkin, A., Charnenok, E., & Krstic, B. (2021). The use of degraded peatlands for biomass production. *Zbornik Matice Srpske Za Prirodne Nauke*, *140*, 103–112. https://doi.org/10.2298/ZMSPN2140103R

Samal, S. (2021). Utilization of red mud as a source for metal ions—A review. *Materials*, *14*(9), 2211. https://doi.org/10.3390/ma14092211

Santini, T. C., Kerr, J. L., & Warren, L. A. (2015). Microbially-driven strategies for bioremediation of bauxite residue. *Journal of Hazardous Materials*, *293*, 131–157. https://doi.org/10.1016/j.jhazmat.2015.03.024

Sardans, J., & Peñuelas, J. (2021). Potassium control of plant functions: Ecological and agricultural implications. *Plants*, *10*(2), 419. https://doi.org/10.3390/plants10020419

Sasmito, S. D., Taillardat, P., Adinugroho, W. C., Krisnawati, H., Novita, N., Fatoyinbo, L., ..., & Lupascu, M. (2025). Half of land use carbon emissions in Southeast Asia can be mitigated through peat swamp forest and mangrove conservation and restoration. *Nature Communications*, *16*(1), 740. https://doi.org/10.1038/s41467-025-55892-0

Sharma, U. C., Datta, M., & Sharma, V. (2025). Chemistry, microbiology, and behaviour of acid soils. *Soil Acidity: Management Options for Higher Crop Productivity*, pp. 121–322. Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-76357-1_3

Sinaga, P. H., Jahari, M., Usman, Istina, I. N., & Sutrisna, N. (2020). Minimum fertilizer for maize cultivation in suboptimal agroecosystem. *IOP Conference Series: Earth and Environmental Science*, *484*(1), 012119. https://doi.org/10.1088/1755-1315/484/1/012119

Singh, Y. V. (2024). *Standard methods for soil, water and plant analysis* (1st ed.). London: CRC Press. https://doi.org/10.1201/9781003534303

Strack, M., Davidson, S. J., Hirano, T., & Dunn, C. (2022). The potential of peatlands as nature-based climate solutions. *Current Climate Change Reports*, *8*(3), 71–82. https://doi.org/10.1007/s40641-022-00183-9

Sulakhudin, Herawatiningsih, R., Krisnohadi, A., Abdillah, A. M., Santi, & Mudim. (2024). Impact of red mud on soil properties and revegetation species growth in bauxite mining land reclamation. *Journal of Degraded and Mining Lands Management*, *12*(1), 6509–6518. https://doi.org/10.15243/jdmlm.2024.121.6509

Surachman, S., Palupi, T., Purwaningsih, P., & Gafur, S. (2024). The effect of biostimulants and red mud on the growth and yield of shallots in post-unlicensed gold mining soil. *Open Agriculture*, *9*(1), 20220325. https://doi.org/10.1515/opag-2022-0325

Syahza, A., Suswondo, Bakce, D., Nasrul, B., Wawan, & Irianti, M. (2020). Peatland policy and management strategy to support sustainable development in Indonesia. *Journal of Physics: Conference Series*, *1655*(1), 012151. https://doi.org/10.1088/1742-6596/1655/1/012151

Taneez, M., & Hurel, C. (2019). A review on the potential uses of red mud as amendment for pollution control in environmental media. *Environmental Science and Pollution Research*, *26*(22), 22106–22125. https://doi.org/10.1007/s11356-019-05576-2

Tanvar, H., & Mishra, B. (2025). Environmental management by recycling of bauxite residue. *Journal of Advanced Manufacturing and Processing*, e70010. https://doi.org/10.1002/amp2.70010

Tong, Z., Hua, P., Zeng, Q., Li, X., Zhang, S., Hu, Z., & Jia, H. (2025). Properties of red mud treated synergistically with citric acid and calcium nitrate and their effects on plant growth after soil conversion. *Journal of Sustainable Metallurgy*, *11*(2), 1658–1670. https://doi.org/10.1007/s40831-025-01073-8

Uda, S. K., Hein, L., & Atmoko, D. (2019). Assessing the health impacts of peatland fires: A case study for Central Kalimantan, Indonesia. *Environmental Science and*

Pollution Research, *26*(30), 31315–31327. https://doi.org/10.1007/s11356-019-06264-x

Vuković, J., Perušić, M., Stopić, S., Kostić, D., Smiljanić, S., Filipović, R., & Damjanović, V. (2024). A review of the red mud utilization possibilities. *Ovidius University Annals of Chemistry*, *35*(2), 165–173. https://doi.org/10.2478/auoc-2024-0021

Wang, M., & Liu, X. (2021). Applications of red mud as an environmental remediation material: A review. *Journal of Hazardous Materials*, *408*, 124420. https://doi.org/10.1016/j.jhazmat.2020.124420

Widiastuti, D. P., Hatta, M., Aziz, H., Permana, D., Santari, P. T., Rohaeni, E. S., ..., & Rakhmani, S. I. W. (2024). Peatlands management for sustainable use on the integration of maize and cattle in a circular agriculture system in West Kalimantan, Indonesia. *Heliyon*, *10*(10), e31259. https://doi.org/10.1016/j.heliyon.2024.e31259

Xu, W., Jin, Y., & Zeng, G. (2024). Introduction of heavy metals contamination in the water and soil: A review on source, toxicity and remediation methods. *Green Chemistry Letters and Reviews*, *17*(1), 2404235. https://doi.org/10.1080/17518253.2024.2404235

Xue, H., Lv, G., & Zhang, T. (2025). Progress of solid waste red mud in the field of ecology and environment. *Water, Air, & Soil Pollution*, *236*(3), 176. https://doi.org/10.1007/s11270-025-07815-4

Xue, J., Gao, S., Fan, Y., Li, L., Ming, B., Wang, K., Xie, R., Hou, P., & Li, S. (2020). Traits of plant morphology, stalk mechanical strength, and biomass accumulation in the selection of lodging-resistant maize cultivars. *European Journal of Agronomy*, *117*, 126073. https://doi.org/10.1016/j.eja.2020.126073

Zhang, S., Yang, X., Hsu, L.-C., Liu, Y.-T., Wang, S.-L., White, J. R., ..., & Rinklebe, J. (2021). Soil acidification enhances the mobilization of phosphorus under anoxic conditions in an agricultural soil: Investigating the potential for loss of phosphorus to water and the associated environmental risk. *Science of the Total Environment*, *793*, 148531. https://doi.org/10.1016/j.scitotenv.2021.148531

Zhou, J.-M. (2024). The relationship between soil pH and geochemical components. *Environmental Earth Sciences*, *83*(13), 402. https://doi.org/10.1007/s12665-024-11711-1

Zhou, Y., Cui, Y., Yang, J., Chen, L., Qi, J., Zhang, L., ..., & Li, B. (2024). Roles of red mud in remediation of contaminated soil in mining areas: Mechanisms, advances and perspectives. *Journal of Environmental Management*, *356*, 120608. https://doi.org/10.1016/j.jenvman.2024.120608