Pertanika J. Trop. Agric. Sci. 49 (4): 1787 - 1809 (2026)

TROPICAL AGRICULTURAL SCIENCE

Journal homepage: http://www.pertanika.upm.edu.my/

Ameliorating Acidity and Nutrient Leaching in Tropical Soils Using Silico-Manganese Slag in Combination with Chemical Fertilisers

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ABSTRACT

High rainfalls and humid temperatures in tropical regions resulted in acidic soils because of excessive leaching of base cations and occupation of iron (Fe^{2+}) and aluminium (Al^{3+}) ions. Silico-manganese slag (SiMn slag) is an alkaline material which could neutralise soil acidity and regulate nutrient leaching. A 30-day leaching study was conducted to determine the effects of SiMn slag and chemical fertilisers (CF) on nutrient leaching in Bekenu series (*Typic Paleudults*). One kilogramme of Bekenu series was mixed with different rates of SiMn slag and CF: T0 = soil only; T1 = SiMn slag only; T2 = soil + 100% CF; T3 = soil + 100% SiMn slag; T4 = soil + 75% SiMn slag + 25% CF; T5 = soil + 50% SiMn slag + 50% CF; and T6 = soil + 25% SiMn slag + 75% CF. The co-application of SiMn slag and CF consistently increased pH and EC of the leachates, which resulted in significantly higher amounts of ammonium (NH_4^+), nitrate (NO_3^-), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) leached. After 30 days of leaching, co-applying SiMn slag and CF increased soil pH, electrical conductivity (EC), exchangeable NH_4^+, Ca^{2+}, and Mg^{2+} by reducing exchangeable acidity and Al^{3+}. We concluded that SiMn slag did not mitigate nutrient leaching, but rather it may have ameliorated acidity to improve nutrient availability. The most suitable combinations are T5 (soil + 50% SiMn slag + 50% CF) and T6 (soil + 25% SiMn slag + 75% CF). Further pot and field studies are recommended to evaluate soil–plant interactions using SiMn slag.

Keywords: Highly weathered, nutrient retention, scheduled waste, silicon, soil fertility and management, Ultisols, *Zea mays* L

ARTICLE INFO

Article history:
Received: 09 June 2026
Accepted: 20 July 2026
Published: 14 August 2026

DOI: https://doi.org/10.47836/pjtas.49.4.10

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e-ISSN: 2231-8542

INTRODUCTION

Excessive nutrient leaching from the soil poses a significant impediment to optimal plant growth and nutrient utilisation, in addition to affecting agricultural productivity, because the plant-available nutrients percolate to the underground below the root zone when prolonged rainfall exceeded field capacity (Lehmann & Schroth, 2003). It is reported that approximately 3.95 billion hectares of land are acidic soils in the world (Easton & Bock, 2016; Rashmi et al., 2017). In the tropical regions, excessive rainfalls and humid temperatures resulted in the formation of highly weathered acidic soils such as Ultisols and Oxisols (Paramisparam et al., 2021). Narro et al. (2001) also pointed out that the global distribution of the Oxisols and Ultisols is in the following order: America (40.9%), Asia (26.4%), Africa (16.7%), Europe (9.9%), and Australia and New Zealand (6.1%). These acidic soils are characterised by low pH levels with an abundance of kaolinite clay minerals, aluminium and iron oxides; low in pH buffering capacity, base saturation, and nutrient availability, as well as prone to nutrient leaching (Kuo et al., 2020; Shamshuddin & Wan, 2011). In Malaysia, approximately 72% of agricultural lands are classified as highly weathered acidic soils, which impair crop productivity because of their low pH (<5.5) and relatively poor fertility due to nutrient imbalance (Jusop & Ishak, 2010).

A promising avenue to address the issue of acidic soils is the exploration of innovative soil amendments that not only mitigate acidity, Al and Fe toxicities, but also improve nutrient retention in acidic soils. Recently, many promising and novel strategies for enhancing the productivity in Malaysian soils, aimed at increasing crop yields and economic income for both small and large-scale farmers, involves soil conditioning through the incorporation of organic and inorganic amendments, have been explored (Hassan et al., 2023; Lee et al., 2021; Ali et al., 2023; Omar et al., 2021; Ch'ng et al., 2019). However, the potential of scheduled waste such as silico-manganese slag (SiMn slag) as a soil amendment to augment the physical, chemical, and biological properties of acidic soils in Malaysia remains unrevealed. Silico-manganese slag is a by-product generated during the production of SiMn alloys, which is primarily used in steel manufacturing, where approximately 15% to 20% of total steel production results in the formation of SiMn slag (Ting et al., 2023; Wu et al., 2007). Notably, the town of Bintulu in Sarawak, Malaysia, is known for its industrial activities, including SiMn production with an annual tonnage of approximately 444,000 tonnes in 2022 (Ting et al., 2023). Despite its industrial significance in construction and building materials, the full potential of SiMn slag, its properties, and its various applications in agriculture remain largely unexplored. In this context, conducting localised research can unveil valuable insights into the characteristics of this slag, its environmental implications, and innovative approaches to manage it effectively, thereby fostering sustainable industrial development in the region.

The reason why SiMn slag is being distinguished as an effective soil conditioner is because of its advantageous qualities, such as neutralising capabilities due to its alkalinity, ease of application, and considerable amounts of alkaline materials such as silicon oxide (26.19% to 47.54%) (Mussawar et al., 2022; Wang et al., 2017b), calcium oxide (9.24% to 29.10%) (Navarro et al., 2020; Wang et al., 2017b), and magnesium oxide (3.70% to 6.91%) (Cheng et al., 2023; Criado et al., 2018) contents. Beyond its liming effects to improve soil pH, SiMn slag is reputed to detoxify soil from excessive Al^{3+} and Fe^{2+} saturations, which can be detrimental to plant roots and inhibit phosphorus (P) uptake by plants (Boguta et al., 2019; Jo et al., 2022). Many research has also reported that the increase of water-soluble Si content in acidic soils not only mobilises P via anion exchange reaction, but it also mitigates P fixation by transforming active Al^{3+} and Fe^{2+} into insoluble hydroxides via the increased pH (Ch'ng et al., 2014; Schaller et al., 2019). Cai et al. (2015) also opined that the inclusion of alkaline materials, which have higher base saturation compared with the unproductive acidic soils, can improve the availability of potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) in addition to immobilising excessive H^+ in the soil solution. Furthermore, SiMn slag contains silicon (Si), a beneficial nutrient known to enhance plant growth and yield by improving resistance to environmental stressors, nutrient imbalances, pathogens, and herbivores (Neu et al., 2017; Sahebi et al., 2015; Wang et al., 2017a). The application of Si-based soil amendments significantly improved growth, development, and reproduction of rice and maize, which are being categorised as Si accumulators (Pozza et al., 2015; Sahebi et al., 2015; Shajarutulwardah et al., 2023). Moreover, applying SiMn slag to mineral soils can release Si to enhance soil properties, including strength, structure, water movement, air circulation, and nutrient retention and availability (Schaller et al., 2019; Schaller et al., 2020).

Based on the aforementioned rationales, there is a dearth of information on the effects of combined use of SiMn slag and chemical fertilisers to mitigate nutrient leaching and improve nutrient retention in acidic soils such as the Bekenu series. Moreover, the nutrient retention and leaching in the acidic soil following the application of SiMn slag are sparsely explored. Thus, it was hypothesised that the use of SiMn slag can neutralise soil acidity, detoxify active Al^{3+} and Fe^{2+} in addition to improving nutrient retention in acidic soils via increased contents of CaO, MgO, and SiO_3^{2-}. The objective of this study was to determine the effect of SiMn slag application combined with chemical fertilisers on nutrient leaching in Bekenu series (*Typic Paleudults*). It is hoped that the inclusion of SiMn slag can reduce the reliance of farmers on the heavy use of chemical fertilisers in sustaining a productive maize farming system via a soil health rejuvenation approach.

MATERIALS AND METHODS

Soil Sampling and Preparation

Based on the United States Department of Agriculture (USDA) soil classification system, the soil used in this leaching experiment was the Bekenu series (*Typic Paleudults*). This soil was selected because it is acidic and commonly used for oil palm, rubber, and black pepper cultivations (Paramananthan, 2020). According to Paramananthan (2020), the Bekenu series is an Ultisol which has fine loamy soil texture with more than 90% silica minerals, and it has a well-drained soil. In terms of parent material, the soil is made up of red-yellow sedimentary rocks with more than 30% ferric oxide, which contributes to its highly acidic nature. Moreover, Shamshuddin & Wan (2011) opined that high rainfall and humid temperatures result in the formation of highly weathered soils prone to leaching of base cations. In terms of microclimate, the soil sampling area has an average annual rainfall, air temperature, and relative humidity of 2,993 mm, 27 °C, and 80%, respectively (Johan et al., 2021). The soil sample was collected using a shovel at an uncultivated area of Universiti Putra Malaysia Sarawak (UPMS) (latitude 03°20 N, longitude 113°07 E). The soil sample was collected in a pedon (1 m length × 1 m width) at 20 cm depth, followed by air-drying, manual crushing, and passing a 2.0 mm sieve prior to the determination of selected physico-chemical properties.

Silico-Manganese Slag Preparation

The silico-manganese slag (SiMn slag) is a scheduled waste from steel production at Pertama Ferroalloys Sdn. Bhd., Bintulu, Sarawak, Malaysia (latitude 03°54 N, longitude 113°31 E). It was selected for amending the nutrient leaching in the Bekenu series because of its alkalinity to neutralise soil acidity and increase the number of exchangeable sites to retain the nutrients. The SiMn slag was randomly collected into gunny sacks using a shovel and then transported to the Soil Science Laboratory under the Department of Crop Science in UPMS for air-drying, manual crushing, and passing through a 2.0 mm sieve before the physico-chemical properties characterisation.

Initial Characterisation of Soil and Silico-Manganese Slag

Before commencing the soil leaching experiment, the physico-chemical properties of the soil and SiMn slag were determined for initial characterisation. Details of the analysis methods for determining the physico-chemical properties of the soil and SiMn slag are summarised in Table 1. The initial physico-chemical properties of the soil and SiMn slag were summarised in Table 2. The prepared sample of SiMn slag was sent to an external laboratory (Chemsain Konsultan Sdn. Bhd., Kuching, Sarawak, Malaysia) for the determination of heavy metals such as lead (Pb), nickel (Ni), cadmium (Cd), chromium (Cr), mercury (Hg), and arsenic (As). The composition and regulatory threshold of each heavy metal are reported in Table 3.

Table 1
Methods used in analysing the physico-chemical properties of soil and silico-manganese slag

No.	Physico-Chemical Analyses	Method	References
1	Soil bulk density	Core ring method	Tan, 2005
2	Soil texture and particle size distribution	Hydrometer method	Bouyoucos, 1962
3	pH in water and potassium chloride (KCl)	Potentiometric method	Peech, 1965
4	Electrical conductivity	Potentiometric method	Peech, 1965
5	Total organic matter	Loss-on-ignition method	Chefetz et al., 1996
6	Total organic carbon	Loss-on-ignition method	Chefetz et al., 1996
7	Cation exchange capacity	Leaching method using 1.0 mol dm^{-3} ammonium acetate at pH 7, followed by steam distillation	Bremner & Keeney, 1965; Cottenie, 1980
8	Total nitrogen	Kjeldhal method	Bremner, 1965; Keeney & Nelson, 1982
9	Exchangeable ammonium and available nitrate	Extraction using 2 mol dm^{-3} KCl, followed by steam distillation	Keeney & Nelson, 1982
10	Total phosphorus and cations	Aqua regia method	Bernas, 1968
11	Available phosphorus	Mehlich's double acid method, followed by the blue colour method	Mehlich, 1953; Murphy & Riley, 1962
12	Exchangeable cations	Mehlich's double acid method, followed by Atomic Absorption Spectroscopy determination	Mehlich, 1953
13	Total titratable acidity, exchangeable aluminium, and hydrogen	Titration method	Rowell, 1994
14	Silicon oxide	Inductively Coupled Plasma	-

Table 2
Initial physico-chemical properties of Bekenu series and silico-manganese slag

Physico-Chemical Properties	Value Obtained	
	Bekenu Series	Silico-Manganese Slag
Soil texture (USDA)	Sand: 48.3% Silt: 24.0% Clay: 27.7% Sandy clay loam	n.d.
Particle size distribution	n.d.	0.05-2.0 mm: 57.32% 0.002-0.05 mm: 4.58% <0.002 mm: 38.10%
Bulk density (g cm^{-3})	1.20	n.d.
pH in water	5.13	8.00
Electrical conductivity (μS cm^{-1})	90	3600

Table 2 (*continued*)

Physico-Chemical Properties	Value Obtained	
	Bekenu Series	Silico-Manganese Slag
	$cmol_{(+)}kg^{-1}$	
Cation exchange capacity	7.70	12.00
Exchangeable acidity	1.21	0.10
Exchangeable Al^{3+}	1.03	0.06
	$mg\ kg^{-1}$	
Exchangeable NH_4^+	28.02	0.70
Available NO_3^-	15.88	1.00
Available P	1.24	0.90
Exchangeable K^+	76.0	240.8
Exchangeable Ca^{2+}	17.1	1391.6
Exchangeable Mg^{2+}	20.4	495.6
	%	
Silicon oxide (%)	n.d.	27.3
Organic matter content	7.24	4.00
Organic carbon content	4.20	2.32

Note. n.d. = not determined

Table 3
Heavy metal composition and regulatory threshold of silico-manganese slag

Heavy Metals	Value Obtained ($mg\ kg^{-1}$)	*Regulatory Threshold ($mg\ kg^{-1}$)
Lead (as Pb)	2.3	36.0
Nickel (as Ni)	8.9	28.9
Cadmium (as Cd)	Not detected (<1.5)	0.09
Chromium (as Cr)	4.2	14.4
Mercury (as Hg)	Not detected (<0.1)	0.42
Arsenic (as As)	4.6	43.0

Note. *The regulatory threshold is referred to the data from the Department of Environment Malaysia (2009)

Soil Leaching Experiment

From the bulked soil, one kilogramme (1 kg) of soil was weighed using an electronic balance in a cylindrical plastic container (15 cm diameter × 12 cm height) perforated with nine holes at the bottom of the container for each replicate. A piece of Whatman Grade 2 filter paper was added at the bottom of the container to prevent the leaching of soil particles during the commencement of the leaching experiment. After the soil physico-chemical characterisation, different rates of SiMn slag and chemical fertilisers (CF) were fixed in accordance with Malaysian Agricultural Research and Development

Institute (MARDI) recommendations for maize (*Zea mays* L.; Thai super sweet hybrid F1 variety) as our test crop for the future greenhouse and field trials. The recommended rates of nitrogen, phosphorus, and potassium sources supplied to the maize plants per hectare basis are 60 kg ha^{-1} N; 60 kg ha^{-1} P_2O_5; 40 kg ha^{-1} K_2O (130 kg ha^{-1} urea; 130 kg ha^{-1} Triple Super Phosphate; 67 kg ha^{-1} Muriate of Potash), respectively (MARDI, 1993). In this soil leaching experiment, based on the planting density of approximately 26,667 maize plants per hectare, the application rate of the mixture of straight fertilisers (urea, TSP, and MOP) was then scaled down to a per-plant basis at 12.26 g. Afterwards, varying rates by 25% (100%, 75%, 50%, 25%, and 0%) on the combined use of SiMn slag and chemical fertilisers were used to determine the effects of the treatments on regulating nutrient leaching in the soil and to reduce the reliance on chemical fertilisers in maize cultivation. Thus, the rates of the SiMn slag and chemical fertilisers were varied at 12.26 g (100%), 9.20 (75%), 6.13 g (50%), and 3.07 g (25%). Moreover, there were two additional treatments in the study to elucidate the treatment effects in this leaching study: soil only (T0) and SiMn slag only (T1). A total of seven treatments were used in this soil leaching experiment, and details of the treatments evaluated are summarised as follows:

- T0: 1 kg soil only
- T1: 1 kg silico-manganese slag only (SiMn slag)
- T2: 1 kg soil + 12.26 g chemical fertilisers (100%)
- T3: 1 kg soil + 12.26 g SiMn slag (100%)
- T4: 1 kg soil + 9.20 g SiMn slag (75%) + 3.07 g chemical fertilisers (25%)
- T5: 1 kg soil + 6.13 g SiMn slag (50%) + 6.13 g chemical fertilisers (50%)
- T6: 1 kg soil + 3.07 g SiMn slag (25%) + 9.20 g chemical fertilisers (75%)

The soil was mixed thoroughly with different rates of SiMn slag and chemical fertilisers, after which the mixture was moistened to 60% water holding capacity of the soil, which represents the field capacity in this leaching experiment. This is equivalent to 300 mL of distilled water, and the moistened soil samples were left overnight. For each experimental unit, a 500 mL beaker was placed under the perforated container for leachate collection at three-day intervals over the 30 days of leaching. The following day, at the start of the soil leaching experiment, another 300 mL of distilled water was poured meticulously onto the moistened soil sample and allowed to leach for three days into the 500 mL beaker for subsequent laboratory analysis. The addition of 300 mL of distilled water was repeated ten times at three-day intervals for leachate collection up to 30 days. Leachates were collected and analysed for selected chemical properties, which include pH, EC, and the leached amounts of nutrients (NH_4^+, NO_3^-, P, K^+, Ca^{2+}, and Mg^{2+}). After the leaching experiment, soil samples were air-dried, manually crushed, and passed through a 2 mm sieve for chemical analyses. The chemical analyses included soil pH in water, pH in KCl, exchangeable acidity and Al^{3+}, electrical conductivity, cation exchange capacity, exchangeable NH_4^+, available NO_3^-, available P, and exchangeable Ca^{2+} and Mg^{2+} using the procedures as described in Table 1.

Experimental Design and Statistical Analysis

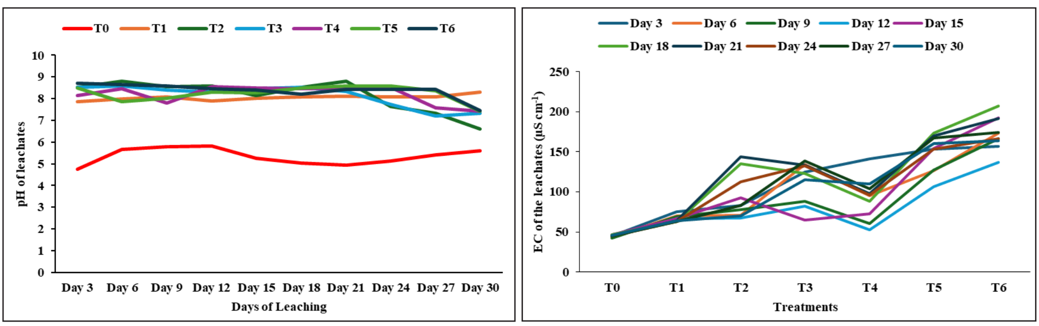
There were seven treatments evaluated in this soil leaching experiment, which were arranged in a Completely Randomised Design (CRD) with three replicates for each treatment. The data were analysed using one-way Analysis of Variance (ANOVA) to determine the treatment effects, followed by mean comparisons using Tukey's HSD test at $p \leq 0.05$ using Statistical Analysis System (SAS) version 9.4.

RESULTS AND DISCUSSION

Co-Application of Silico-Manganese Slag and Chemical Fertilisers on pH and Electrical Conductivity of Leachates

The pH of leachates for the SiMn slag only (T1) and the soils treated with SiMn slag and chemical fertilisers (T2, T3, T4, T5, and T6) exceeded 7, whereas that of the soil only (T0) was acidic (Figure 1a). Although it was observed that the pH of leachates from the soil with sole application of chemical fertilisers (T2) was above 7 in the initial days of leaching, which could be due to urea hydrolysis (Hamidi et al., 2021), the pH of leachate in T2 gradually decreased to 6.61 at day 30 of leaching. The findings suggest that the alkalinity of SiMn slag not only neutralises acidity and increases the pH of soil solution, but it also maintains the soil pH over 30 days of leaching (Ng et al., 2024b; Ng et al., 2022). Moreover, the dissolution of SiMn slag releases K^+, Ca^{2+}, Mg^{2+}, Na^+, and SiO_4^{4-} to increase the pH of leachates (Antonangelo et al., 2017; Opala et al., 2012; Ramos et al., 2006; Zhang et al., 2016), thus impeding Al^{3+}, Fe^{2+}, and Mn^{2+} hydrolysis reactions from producing H^+. Notably, the pH of leachates from soil only (T0) increased from day 6 to day 12, followed by a decrease in the pH of leachates on day 15 to day 21. In the soil solution, the dissolution of silicate minerals in the Bekenu series may have released SiO_4^-, which hydrolyses to form silicic acid (H_4SiO_4) and releases OH^- ions to neutralise free H^+ ions (Elisa et al., 2015). This could account for the pH increase of leachate in T0 from day 6 to day 12.

In Figure 1b, the soil only treatment (T0), consistently recorded the lowest EC throughout the experiment. The EC of leachates for T0 increased from 42.77 µS cm^{-1} on day 6 to 46.50 µS cm^{-1} on day 15 and decreased to 44.70 µS cm^{-1} on day 21, 44.50 µS cm^{-1} on day 24, and a slight increase on day 30 (45.47 µS cm^{-1}). The lowest EC in T0 was due to the low base cation saturations because ferric oxide is the parent material of the Bekenu series that is weathered into kaolinite clay minerals, which have low nutrient holding capacity (Paramisparam et al., 2021). On the contrary, the EC of leachates from SiMn slag (T1) were higher compared with soil only (T0) over 30 days of leaching, which could be due to the dissolution of SiMn slag to release K^+, Ca^{2+}, Mg^{2+}, Na^+, and SiO_4^{4-} into the soil solution, suggesting that SiMn slag had higher EC compared with the Bekenu series. Regardless of the application rate of SiMn slag, the EC of leachates did not exceed the salinity threshold (4000 µS m^{-1}), indicating that the application rates of SiMn slag used in this leaching experiment will not cause salinity problems in the cropping system (USDA, 2011). Moreover, it was noted that the EC of leachates from the soils applied with chemical fertilisers (T2, T4, T5, and T6) were higher compared with T0 and T1. This finding implies that the combined use of chemical fertilisers such as urea, TSP, and MOP may significantly influence the EC of soil solution.



(a) (b)

Figure 1. (a) pH and (b) electrical conductivity of leachates in relation to treatments over thirty days of leaching
Note. T0 = Soil only; T1 = SiMn slag only; T2 = Soil + 100% CF; T3 = Soil + 100% SiMn slag; T4 = Soil + 75% SiMn slag + 25% CF; T5 = Soil + 50% SiMn slag + 50% CF; T6 = Soil + 25% SiMn slag + 75% CF

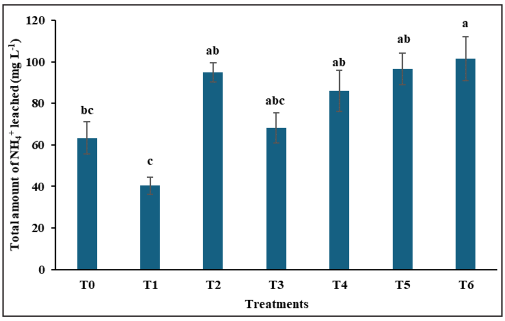
Co-Application of Silico-Manganese Slag and Chemical Fertilisers on Nutrients in the Leachates

The total amounts of NH_4^+ and NO_3^- leached were lower for the SiMg slag only (T1) compared with those of the soil with sole application of chemical fertilisers (T2) and the combined use of SiMn slag and chemical fertilisers (T4, T5, and T6) (Figures 2a and 2b). This is because the SiMn slag had lower exchangeable NH_4^+ (0.7 mg kg^{-1}) and available NO_3^- (1.0 mg kg^{-1}) compared with those of the Bekenu series at 28.02 mg kg^{-1} and 15.88 mg kg^{-1}, respectively (Table 2), suggesting that the combined use of nitrogen source fertilisers and SiMn slag is essential for optimum maize growth and productivity. It was observed that the total amount of NH_4^+ leached from the soils amended with 25% SiMn slag and 75% chemical fertilisers (T6) was higher compared with T0, whereas there is no significant difference between the cumulative amounts of NH_4^+ leached from the SiMn slag (T1) and the soil treated with 12.26 g of SiMn slag (T3), as presented in Figure 2a. This finding suggests that the NH_4^+ and NO_3^- availability in the soil solution was influenced by the chemical fertilisers rather than SiMn slag.

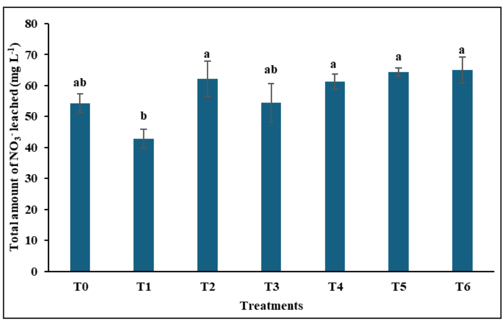
The significantly higher amounts of NH_4^+ and NO_3^- leached are indications of increased N availability in the soil solution, which could be due to the higher pH and EC of the leachates from the soils amended with SiMn slag and chemical fertilisers. The pH and EC are indications of the increased leached amounts of NH_4^+ and NO_3^- because this finding is in agreement with the findings of Neina (2019) and Zhang et al. (2018) who reported that the improved soil pH can mineralise organic N into inorganic NH_4^+ and NO_3^- in the soil solution. This suggests that SiMn slag can also increase N availability in acidic soils for optimum crop uptake through improved soil pH.

Unexpectedly, although it is reported that the increased pH improves microbial activities for mineralising P in the soils (Mehnaz et al., 2019; Malik et al., 2012; Opala et al., 2012), the inclusion of SiMn slag and chemical fertilisers did not significantly influence the total amounts of P leached over 30 days of leaching (Figure 2c). This is because SiMn slag had lower available P (0.90 mg kg^{-1}) compared with that of the soil (1.24 mg kg^{-1}) (Table 2). Moreover, the availability of P in soil solution could be affected by active Al^{3+}, Fe^{2+}, Ca^{2+}, and Mg^{2+}. In acidic soils (T0), active Al^{3+} and Fe^{2+} can adsorb with P (Boguta et al., 2019; Ifansyah, 2014; Zu et al., 2012), whereas the increased concentrations of Ca^{2+} and Mg^{2+} via the inclusion of SiMn slag can precipitate with plant-available P in the soil solution (Chien et al., 2012; Patle et al., 2019). These findings suggest that the effects of Al^{3+}, Fe^{2+}, Ca^{2+}, and Mg^{2+} might have diminished the effects of SiMn slag on improving P availability in the soil solution, regardless of treatment.

Generally, the total amounts of K^+, Ca^{2+}, and Mg^{2+} in the leachates over 30 days of leaching from the soils amended with SiMn slag and chemical fertilisers (particularly in T5 and T6) were higher compared with those of soil only (T0) as presented in Figures 3a, 3b, and 3c. The lowest total amounts of K^+, Ca^{2+}, and Mg^{2+} leached from T0 were due to the acidic nature of the Bekenu series. Compared with the soils with the sole application of chemical fertilisers (T2) (100% CF), the higher total amounts of K^+ leached from the soils treated with 50% SiMn slag and 50% CF (T5) and 25% SiMn slag and 75% CF (T6) suggest that the leaching of K^+ could be due to the antagonistic relationship between K^+ and Ca^{2+}. This finding is in agreement with that of Malvi (2011), who reported that the inclusion of amendments with high Ca^{2+} content can result in increased K^+ leaching due to the cation displacement process. Compared with T5 and T6, the significantly lower total amounts of K^+, Ca^{2+}, and Mg^{2+} leached from the soils treated with the sole application of SiMn slag (T3) also suggest that the dissolution of SiMn slag releases extremely low amounts of base cations over 30 days of leaching, although it was hypothesised that the SiMn slag can contribute to the increased amounts of base cations in the leachates.



(a)



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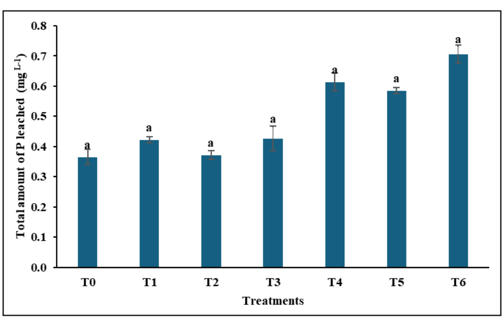
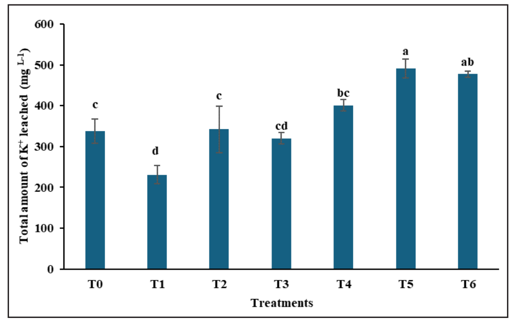


(c)

Figure 2. Total amount of (a) ammonium; (b) nitrate; and (c) phosphate ions in the leachates in relation to treatments after thirty days of leaching. Different letters indicate significant mean differences using Tukey's HSD test at $p \leq 0.05$. The error bars refer to ± standard error of three replicates

Note. T0 = Soil only; T1 = SiMn slag only; T2 = Soil + 100% CF; T3 = Soil + 100% SiMn slag; T4 = Soil + 75% SiMn slag + 25% CF; T5 = Soil + 50% SiMn slag + 50% CF; T6 = Soil + 25% SiMn slag + 75% CF



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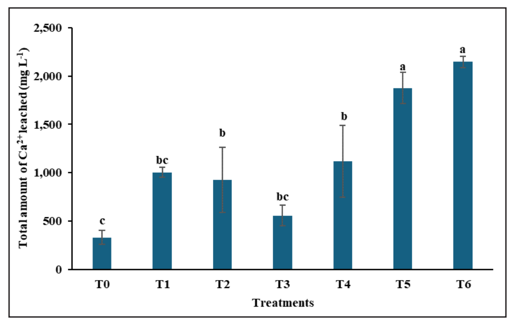
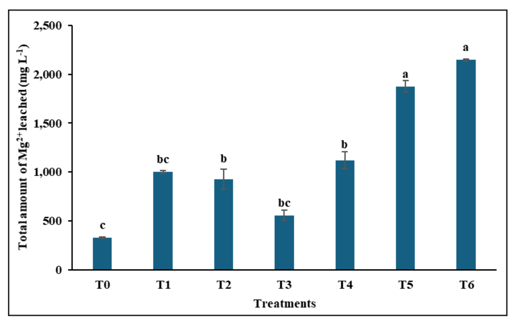


(b)



(c)

Figure 3. Total amount of (a) potassium; (b) calcium; and (c) magnesium ions in the leachates in relation to treatments after thirty days of leaching. Different letters indicate significant mean differences using Tukey's HSD test at $p \leq 0.05$. The error bars refer to ± standard error of three replicates

Note. T0 = Soil only; T1 = SiMn slag only; T2 = Soil + 100% CF; T3 = Soil + 100% SiMn slag; T4 = Soil + 75% SiMn slag + 25% CF; T5 = Soil + 50% SiMn slag + 50% CF; T6 = Soil + 25% SiMn slag + 75% CF

Co-Application of Silico-Manganese Slag and Chemical Fertilisers on Soil pH, Exchangeable Acidity, and Aluminium After Thirty Days of Leaching

The SiMn slag (T1) had the highest pH in water and KCl, followed by the soil pH in water and KCl of the soils amended with SiMn slag (T3, T4, T5, and T6), which were in the range of 6.31 to 6.59 and 4.74 to 5.15, respectively (Figures 4a and 4b). On the contrary, the pH in water and KCl of the soil only without any amendment (T0) were the lowest, whereas the pH and water and KCl of the soils amended with 100% chemical fertilisers (T2) were significantly lower compared with T3, T4, T5, and T6. This finding indicates that the alkalinity and application rates of the SiMn slag used in this study can ameliorate soil acidity and significantly improve soil pH.

The significant increment in soil pH following the application of SiMn slag could be related to the dissolution of calcium oxide (CaO), which can react with the H^+ in the soil solution to produce Ca^{2+} and water (Navarro et al., 2020; Navarro et al., 2017; Wang et al., 2017b). Moreover, the addition of amendments with higher saturations of base cations (K^+, Ca^{2+}, and Mg^{2+}) compared with the Bekenu series can immobilise active H^+ (Cai et al., 2015). When SiMn slag was incorporated into acidic soils, the dissolution of SiO_2 releases OH^- into the soil solution to elevate soil pH (Chong et al., 2022; Ning et al., 2016). This is because the increase of silicon-oxygen tetrahedron (SiO_4^{4-}) in the Bekenu series causes the formation of monosilicic acid (H_4SiO_4) via hydrolysis, where one mole of SiO_4^{4-} reacts with four moles of water to produce another four moles of OH^- (Antonangelo et al., 2017; Sahebi et al., 2015; Sugama & Pyatina, 2015).

Compared with soil only without any amendment (T0), the increased pH also resulted in reduced exchangeable acidity and Al^{3+} in the soils amended with SiMn slag and chemical fertilisers (T3, T4, T5, and T6) (Figures 4c and 4d). For example, the exchangeable acidity in T3, T4, T5, and T6 had significantly decreased to a range of 0.21 to 0.29 $cmol_{(+)}\ kg^{-1}$ compared with T0 at 1.00 $cmol_{(+)}\ kg^{-1}$ (Figure 4c). Furthermore, compared with the exchangeable Al^{3+} at 0.79 $cmol_{(+)}\ kg^{-1}$ (T0), the amendments in T3, T4, T5, and T6 significantly reduced soil exchangeable Al^{3+} to values ranging from 0.05 $cmol_{(+)}\ kg^{-1}$ to 0.14 $cmol_{(+)}\ kg^{-1}$ (Figure 4d).

The reduced soil exchangeable acidity and Al^{3+} are related to the alkalinity of SiMn slag, which is demonstrated by the significantly higher pH of SiMn slag (T1) in Figures 4a and 4b. The value of exchangeable Al^{3+} below the Al toxicity threshold of 0.8 $cmol_{(+)}\ kg^{-1}$ was due to the transformation of active exchangeable Al^{3+} in the soil solution into insoluble Al hydroxide ($Al(OH)_3$) via precipitation (Moir & Moot, 2014; Yerima et al., 2020). In addition, the impaired Al hydrolysis was due to a significant increase in soil pH, where the continuous dissolution of SiMn slag can increase the pH buffering capacity of the Bekenu series to prevent a drastic increase in active H^+ in the soil solution over time (Chong et al., 2022; Pavlů et al., 2021). The reaction of $Al(OH)_3$ with Si released from

SiMn slag leads to the formation of stable aluminium silicate ($Al_2O_3 \cdot 6SiO_2$) to prevent the reverse reaction of $Al(OH)_3$ into toxic Al^{3+}, which can further impair the production of H^+ via Al hydrolysis (Jo et al., 2022).

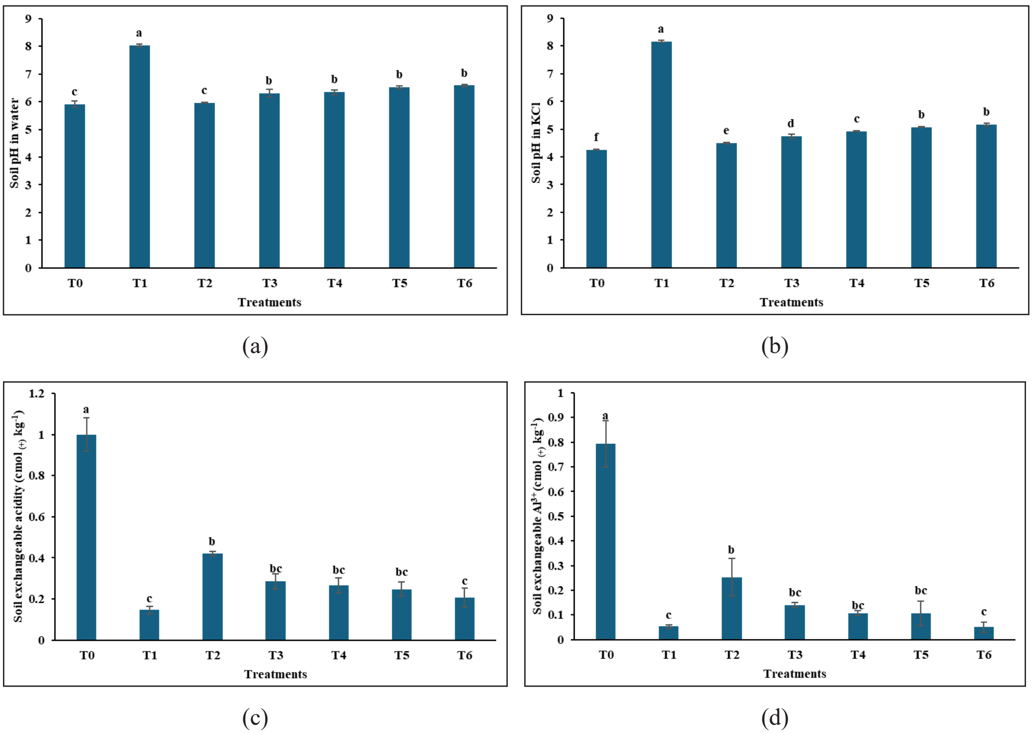
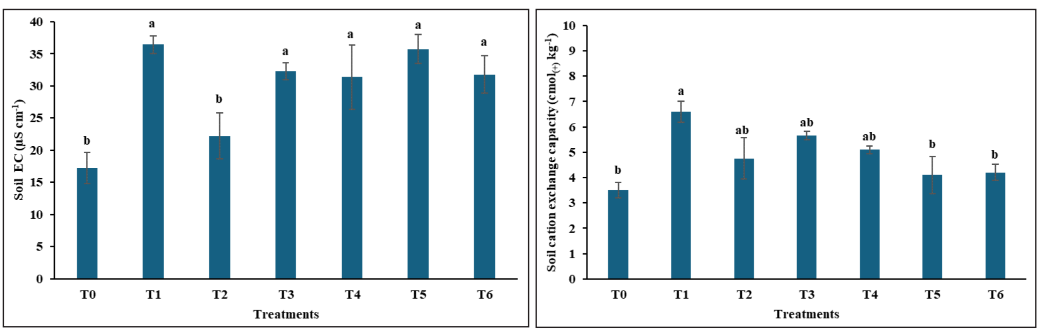


Figure 4. Soil (a) pH in water; (b) pH in potassium chloride; (c) exchangeable acidity; and (d) exchangeable aluminium in relation to treatments over thirty days of leaching. Different letters indicate significant mean differences using Tukey's HSD test at $p \leq 0.05$. The error bars refer to ± standard error of three replicates
Note. T0 = Soil only; T1 = SiMn slag only; T2 = Soil + 100% CF; T3 = Soil + 100% SiMn slag; T4 = Soil + 75% SiMn slag + 25% CF; T5 = Soil + 50% SiMn slag + 50% CF; T6 = Soil + 25% SiMn slag + 75% CF

Co-Application of Silico-Manganese Slag and Chemical Fertilisers on Soil Electrical Conductivity, Cation Exchange Capacity, and Nutrient Availability After Thirty Days of Leaching

In Figure 5a, the EC significantly increased in the soils added with SiMn slag and chemical fertilisers (T3, T4, T5, and T6) compared with soil only (T0) due to the presence of higher exchangeable K^+, Ca^{2+}, and Mg^{2+} in the SiMn slag, as demonstrated in T1. The significant increase in soil EC is related to the increased concentrations of soluble salts such as Na^+, K^+, Ca^{2+}, Mg^{2+}, CO_3^{2-}, and NO_3^- (Gondek *et al.*, 2020). Notably, regardless of treatment, the soil EC did not exceed the salinity threshold of 4000 µS cm^{-1}. Therefore, this finding suggests that the application rates of SiMn slag used for the acidic soils in this study will not affect nutrient availability, microorganism activities, and crop growth (USDA, 2011).

Although the cation exchange capacity (CEC) of SiMn slag (T1) was significantly higher compared with soil only (T0), the inclusion of SiMn slag and/or chemical fertilisers (T2, T3, T4, T5, and T6) did not significantly improve the CEC of Bekenu series, regardless of the SiMn slag rate (Figure 5b). According to Aprile & Lorandi (2012) and Sdiri *et al.* (2012), the higher CEC can retain higher amounts of essential nutrients for optimum timely crop uptake, where the increased soil base saturation and pH can improve soil CEC via the increased number of negatively charged sites on the surface of alkaline materials added. Therefore, based on these findings, we concluded that the rates of SiMn slag should be further increased to improve the CEC of the Bekenu series.



(a) (b)

Figure 5. Soil (a) electrical conductivity and (b) cation exchange capacity in relation to treatments over thirty days of leaching. Different letters indicate significant mean differences using Tukey's HSD test at $p \leq 0.05$. The error bars refer to ± standard error of three replicates

Note. T0 = Soil only; T1 = SiMn slag only; T2 = Soil + 100% CF; T3 = Soil + 100% SiMn slag; T4 = Soil + 75% SiMn slag + 25% CF; T5 = Soil + 50% SiMn slag + 50% CF; T6 = Soil + 25% SiMn slag + 75% CF

After 30 days of leaching, exchangeable NH_4^+ in the soils with the sole application of chemical fertilisers only (T2) and the application of SiMn slag or/and chemical fertilisers (T3, T4, T5, and T6) was significantly higher compared with the soil only without any amendment (T0) (Figure 6a). This indicates that the significant improvement of NH_4^+ availability in the acidic soils was due to the application of chemical fertilisers because the SiMn slag (T1) had significantly lower exchangeable NH_4^+ compared with T0. This finding indicates that additional N source fertilisers will be needed to meet crop N requirements.

Interestingly, the combined use of SiMn slag and chemical fertilisers did not significantly affect soil available NO_3^- after 30 days of leaching (Figure 6b). This could be explained by the reduced nitrification, where the higher exchangeable NH_4^+ in the soils following the incorporation of SiMn slag and chemical fertilisers, because the application of urea in T2, T4, T5, and T6 did not show a clear increasing trend in NO_3^-. Besides, the insignificant increase of soil available NO_3^- could be speculated by the high mobility of NO_3^- in soils (Gao et al., 2019; Zhang et al., 2020). The negatively charged sites on the soil colloids tend to repel NO_3^- (Lehmann & Schroth, 2003). Ng et al. (2024a) and Ng et al. (2021) also reported that the increased soil CEC retained a higher amount of exchangeable NH_4^+ to prevent nitrification. However, the use of SiMn slag did not significantly improve soil CEC; thus, the increase in pH is the dominant factor which prevents nitrification rather than CEC. Furthermore, SiMn slag has low inorganic N contents for both NH_4^+ and NO_3^-, thus the addition of nitrogen-based fertilisers is essential to improve soil N availability.

Similar with the total amount of P leached over 30 days of leaching (Figure 2c), the insignificant differences of soil available P (Figure 6c) following application of SiMn slag could be due to the low inherent P content in SiMn slag and the diminished effects by Al^{3+}, Fe^{2+} in the acidic soils (T0) as well as Ca^{2+} and Mg^{2+} in the soils with the inclusion of SiMn slag. Additionally, the sorbed P on Fe minerals was mobilised by Si released from the SiMn slag, potentially increasing P availability in the soil. For example, Ng et al. (2024b) and Schaller et al. (2019) claimed that Si has a higher affinity for binding with soil Fe minerals compared with P, where the P mobilisation positively correlates with increasing Si availability. Conversely, the insignificant differences in available P among the treatments could be due to the low dissolution of SiMn slag to release Si and insufficient application rates of SiMn slag used for P mobilisation in this soil leaching experiment.

At the end of the leaching experiment, the soil exchangeable Ca^{2+} significantly increased in the soils amended with SiMn slag or/and chemical fertilisers (T3, T4, T5, and T6) to a range of 1.42 mg kg^{-1} to 2.93 mg kg^{-1} compared with the soil only (T0) at 0.04 mg kg^{-1} (Figure 6d). Based on Figure 6e, soil exchangeable Mg^{2+} for T3 (0.31 mg kg^{-1}), T4 (0.38 mg kg^{-1}), T5 (0.47 mg kg^{-1}), and T6 (0.54 mg kg^{-1}) significantly increased compared with T0 (0.08 mg kg^{-1}) after 30 days of leaching. The increase in soil exchangeable Ca^{2+} and Mg^{2+} was because of the considerable inherent contents of the CaO and magnesium oxide (MgO) in the SiMn slag (Table 2). This finding is further supported by findings which reported that the SiMn slag has considerable contents of CaO and MgO, ranging from 9.24% to 29.10% and 3.70% to 6.91%, respectively (Cheng et al., 2023; Criado et al., 2018; Navarro et al., 2020; Navarro et al., 2017; Wang et al., 2017b). Therefore, we concluded that the use of SiMg slag can increase the base saturations in acidic soils to immobilise H^+ and mitigate Al and Fe hydrolysis to improve soil pH over time.

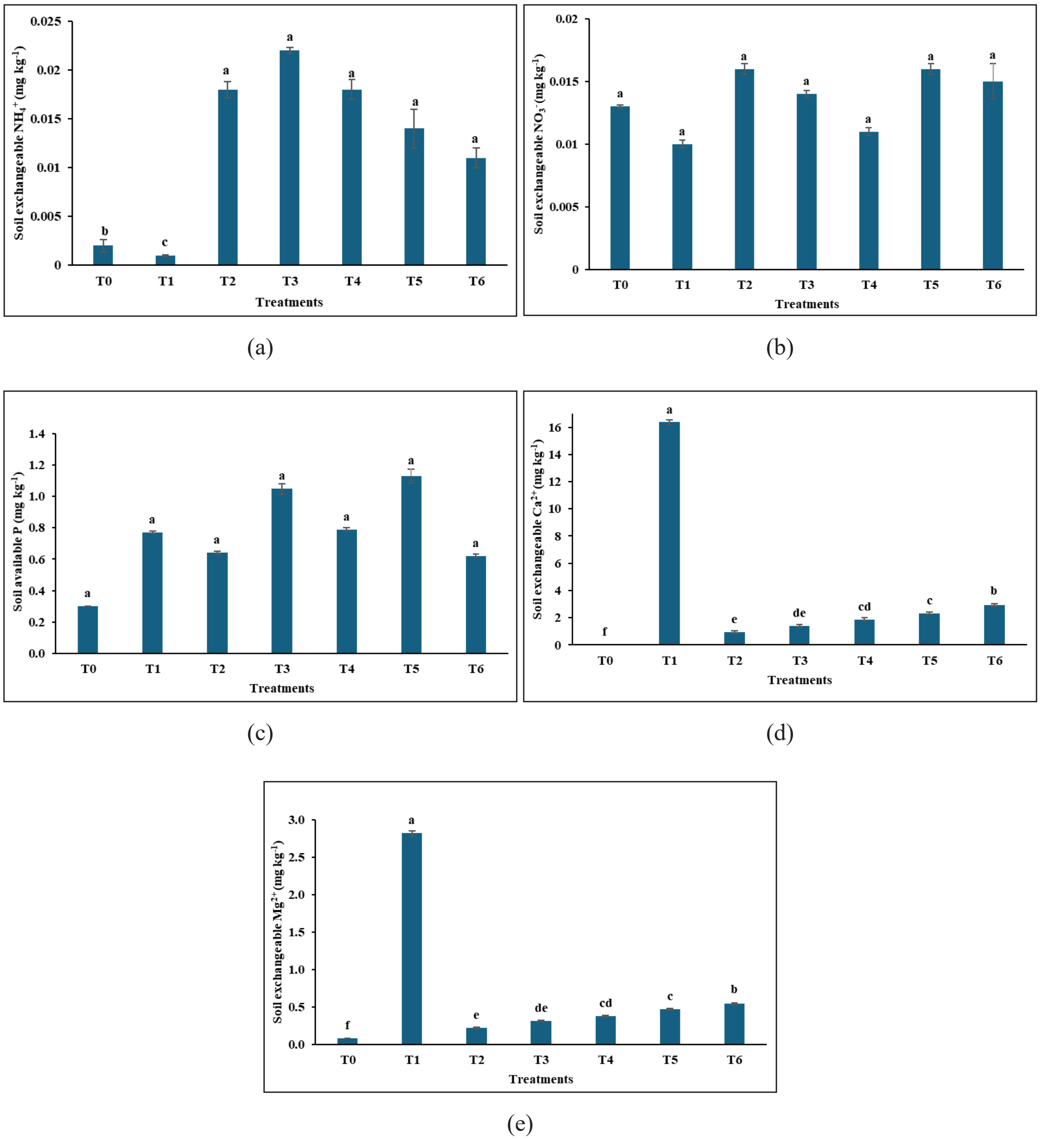


Figure 6. Soil (a) ammonium; (b) nitrate; (c) phosphorus; (d) calcium; and (e) magnesium in relation to treatments over thirty days of leaching. Different letters indicate significant mean differences using Tukey's HSD test at $p \leq 0.05$. Different letters indicate significant mean differences using Tukey's HSD test at $p \leq 0.05$. The error bars refer to ± standard error of three replicates

Note. T0 = Soil only; T1 = SiMn slag only; T2 = Soil + 100% CF; T3 = Soil + 100% SiMn slag; T4 = Soil + 75% SiMn slag + 25% CF; T5 = Soil + 50% SiMn slag + 50% CF; T6 = Soil + 25% SiMn slag + 75% CF

CONCLUSION

Co-applying SiMn slag and chemical fertilisers can improve soil pH, EC, exchangeable NH_4^+, Ca^{2+}, and Mg^{2+} in addition to suppressing exchangeable acidity and Al^{3+} of the

Bekenu series because of the alkalinity and liming effects (Ca^{2+} and Mg^{2+}) of SiMn slag. After 30 days of leaching, the higher amounts of NH_4^+, NO_3^-, K^+, Ca^{2+}, and Mg^{2+} leached from the amended soils are reflected by higher pH and EC of the leachates. This finding indicates that our approach did not mitigate nutrient leaching but rather improved the nutrient availability in the soil solution for rapid crop uptake. Based on our findings, the most suitable combinations are T5 (50% SiMn slag + 50% CF) and T6 (25% SiMn slag + 75% CF) per kilogram of soil because of their consistent effects on improving soil pH, exchangeable NH_4^+, Ca^{2+}, Mg^{2+}, and EC by suppressing exchangeable acidity and Al^{3+}. The use of SiMn slag as a scheduled industrial waste provides fundamental information to determine the effects of the suitable combinations uncovered by this present study on nutrient leaching and retention in the tropical acidic soils. Further pot and field research involving maize plants for revealing soil-plant interactions is recommended to further validate if the application of SiMn slag can reduce fertiliser dosage in the maize farming system.

ACKNOWLEDGEMENT

The authors would like to acknowledge Universiti Putra Malaysia Sarawak for providing the research facilities. Our appreciation is also extended to colleagues and staff of Universiti Putra Malaysia Sarawak (Malaysia) and Universiti Islam Sultan Sharif Ali (Brunei Darussalam) for the technical support. We would like to thank Pertama Ferroalloys Sdn. Bhd. (Sarawak, Malaysia) and Sarmag Resources Sdn. Bhd. (Sarawak, Malaysia) for their financial support and collaboration. We would like to express our greatest gratitude to Dr. Roland Kueh Jui Heng for his contribution and supervision in this project.

FUNDING

This research was funded by Pertama Ferroalloys Sdn. Bhd., Sarawak (Grant number: 6300922) and Sarmag Resources Trading Sdn. Bhd., Sarawak, Malaysia (Grant number: 6300921).

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