CHILEAN JOURNAL of AGRICULTURAL RESEARCH

CHILEANJAR
CHILEAN JOURNAL of AGRICULTURAL RESEARCH

RESEARCH ARTICLE

Si-Humate as soil ameliorant to improve the properties of acid sulfate soil, growth, and rice yield

Eni Maftu'ah[1*], Muhammad Saleh[1], Yiyi Sulaeman[1], Khairatun Napisah[1], Rusmila Agustina[1], Mukhlis Mukhlis[1], Khairil Anwar[1], Rina Dirgahayu Ningsih[1], Masganti Masganti[1], Puspita Harum Maharani[1], Syaiful Asikin[1], Vicca Karolinoerita[2], Nur Wakhid[3], Afiah Hayati[4], and Yuli Lestari[5]

[1]National Research and Innovation Agency Republic of Indonesia, Research Center for Food Crops, Jl. Raya Jakarta-Bogor km 46, Cibinong, Bogor 16911, West Java, Indonesia.
[2]National Research and Innovation Agency Republic of Indonesia, Research Center for Geospatial, Jl. Raya Jakarta-Bogor km 46, Cibinong, Bogor 16911, West Java, Indonesia.
[3]National Research and Innovation Agency Republic of Indonesia, Research Center for Ecology and Ethnobiology, Jl. Raya Jakarta-Bogor km 46, Cibinong, Bogor 16911, West Java, Indonesia.
[4]Lambung Mangkurat University, Agriculture Faculty, Banjarbaru, South Kalimantan, Indonesia.
[5]Indonesia Swampland Agriculture Standardization Institute, Jl. Karet, Loktabat Utara, Banjarbaru, South Kalimantan, Indonesia.
[*]Corresponding author (enim002@brin.go.id).
Received: 16 November 2023; Accepted: 3 January 2024, doi:10.4067/S0718-58392024000200267

ABSTRACT

Soil ameliorants play a crucial role in enhancing soil fertility and rice (*Oryza sativa* L.) production in acid-sulfate soils. This research aims to study the impact of Si-humic ameliorants on soil chemical properties, plant growth, Fe levels, and rice production in acid-sulfate soil. The experiments were conducted at the Laboratory and Greenhouse of the Indonesia Swampland Agricultural Research Institute. The greenhouse experiment adopted a factorial RCBD with Factor 1 representing the ameliorant formula type: 100% lime (F0), 30% commercial humate+30% rice husk ash+40% lime (F1), 30% water hyacinth humate+30% rice husk ash+40% lime (F2), 30% water hyacinth humate+30% rice husk biochar+40% lime (F3), 30% commercial humate+30% rice husk biochar+40% lime (F4), and control without ameliorant. Factor 2 represents dosage of soil ameliorant: 0, 1, 2, and 4 t ha^{-1}. Observations included soil properties such as pH, exchangeable Fe, available P, plant growth, Fe toxicity, yield, and yield components. Silicon-humic soil ameliorant demonstrated the ability to enhance soil pH from 3.16 to 3.63, available P from 6.12 to 30.16 mg kg^{-1}, and decrease Fe 690 to 371 mg kg^{-1}. Specifically, the F3 Si-humate formulation alleviated Fe toxicity, enhanced P availability, promoted rice growth, and improved yield. The application of 4 t ha^{-1} Si-humate F3 had the best effect in increasing grain yield by 4.22 g pot^{-1} compared to the control. The application of Si-humate F3 not only improved soil quality and increased rice yields but also reduced the need for lime, contributing to the potential maintenance of soil health.

Key words: Iron toxicity, *Oryza sativa*, pyrite oxidation, risk husk biochar, soil acidity.

INTRODUCTION

Tidal swamp land, totaling 8.92 million hectares, holds significant potential for agricultural development (Ritung et al., 2015). Nevertheless, the overall productivity of this land is hindered by various biophysical factors, such as elevated soil acidity resulting from pyrite oxidation, limited nutrient availability in the soil, and the presence of toxic substances like Al, Fe, and hydrogen sulfide (H_2S). Pyrite oxidation leads to a notable increase in soil acidity, restricted nutrient availability, especially for P, and heightened Fe toxicity, making soil fertility unsuitable for successful plant cultivation.

Pyrite oxidation triggers the production of sulfuric acid, leading to extreme soil acidity and causing a shortage of crucial nutrients, particularly P. The generated sulfuric acid further releases Fe species (Fe^{2+}, Fe^{3+}), Al (Al^{3+}), and other potentially toxic elements into the soil and water systems (Nordmyr et al., 2008). According to Shamshuddin et al. (2004), acid sulfate soil could become suitable for crop production if soil properties are enhanced and fertility is increased.

A strategy used to enhance the fertility of acid sulfate soils involves soil amelioration. Soil ameliorant materials play a crucial role in improving both the physical and chemical properties of the soil. They contribute to the increase in soil pH, boost nutrient availability, improve soil water content, and foster better plant growth. Lime, a commonly employed ameliorant material, is known for its effectiveness in enhancing and increasing the productivity of acid sulfate soils. The application of lime has been shown to elevate the soil pH of acid sulfate soil from 3.26 to 4.37 (Shamshuddin et al., 2013). Lime, beyond its role in elevating soil pH, also serves to inactivate Fe and Al. To decrease Al^{3+} levels in acid sulfate soil from 12.75 to 2.37 cmol kg^{-1}, 8 t ha^{-1} dolomite is required while reducing it from 4.18 to 0.69 cmol kg^{-1} necessitates 4 t ha^{-1} dolomite. Furthermore, the application of 4 t ha^{-1} dolomite can effectively lower Fe levels from 189 to 86 ppm (Panhwar et al., 2014). Given the substantial lime requirements to mitigate acidity and Al activity, the use of lime alone becomes impractical. Therefore, incorporating other ingredients becomes essential to optimize the efficacy of agricultural lime.

Silica contributes significantly to enhancing the resistance of rice plants against stem borers and brown planthoppers. The plants display increased stability, minimizing the risk of toppling. The utilization of Si serves to diminish the uptake of Fe and Al, particularly in toxic conditions. The utilization of silica extracted from rice husks as an adsorbent, particularly for selectively adsorbing metal ions, has been widely used. Several research results show that Si has an effect in reducing the level of Al and Fe toxicity in the soil, reducing the Fe content on the surface of rice roots, and reducing Fe uptake in lowland rice plants by increasing the oxidative strength of the roots. Providing Si elements in the soil increases the tolerance of rice plants to various biotic stresses (Perez et al., 2014; Debona et al., 2017) and abiotic stresses such as toxic metals (Song et al., 2014; Abbas et al., 2015; Sanglard et al., 2016; Coskun et al., 2019). The element Si can reduce the effects of toxicity on rice plants by reducing Fe concentrations in leaf and root tissue and increasing the activity of the antioxidant system (Dufey et al., 2014).

Humic material, serving as a soil ameliorant, interacts with metal ions, including Al and Fe, forming chelates that enhance soil quality. Humate, a component of humic materials, contributes to the improvement of soil's physical properties (Tregubova et al., 2019). In acid sulfate soils, the application of humic materials is pivotal due to their capacity to suppress Fe solubility through a chelating mechanism. Research by Bourbonniere and Creed (2006) highlights that humates and fulvic contain carboxyl and phenolic groups, functioning as organic colloids that contribute to the soil's negative charge. This functional group is crucial in determining the chelation reaction of Fe and Al in acid sulfate soil. This research aims to study the characteristics of soil ameliorants and the impact of various soil ameliorant formulas on soil chemical properties, plant growth, Fe levels, and rice production in acid sulfate soils.

MATERIALS AND METHODS

The research was carried out in the laboratory and greenhouse of Indonesia Swampland Agricultural Research Institute from January to December 2022. The laboratory activities focused on characterizing and formulating soil ameliorants, as well as conducting soil and plant analyses. The greenhouse phase aimed to assess the effectiveness of various formulated soil ameliorants in terms of their impact on growth, nutrient levels in rice (*Oryza sativa* L.) plants, and the mitigation of Fe toxicity in acid sulfate soil media.

The soil ameliorant materials used encompass a combination of humic and silica sources along with lime. The humic material originates from two distinct sources, namely water hyacinth compost and commercially produced humate (Indobiotec Agro, Malang, Indonesia). Silicon is sourced from both rice husk ash and rice husk biochar.

Characterization of soil ameliorant materials

In this study, the soil ameliorants utilized included agricultural lime, ash, biochar, and commercial humate. The process of determining the proportion of each component per unit weight was termed formulation. The aim of formulating soil ameliorants was to enhance their effectiveness in improving the chemical properties of acid sulfate soils. Based on preliminary research results, the formulated blend demonstrated higher effectiveness compared to individual ingredients (Maftu'ah et al., 2023). Prior to formulation, each material underwent characterization for various chemical properties, and the results are presented in Tables 1 and 2.

Table 1. Characteristics of soil ameliorant materials. HA: Humic acid; FA: fulvic acid; TP: total P; OC: organic C; TN: total N.

	HA	FA	Pb	Cd	Cr	Ni	pH	Na	TP	OC	TN	SiO_2
	— % —		——— µg kg^{-1} ———					——— % ———				
Commercial humate	5.34	2.35	26.71	1.79	0.38	0.21		0.05	0.89	20.27	1.60	-
Water hyacinth humate	1.48	0.93	20.93	1.62	0.67	0.18		0.01	0.02	18.56	0.91	-
Biochar rice husk	-	-	-	-	-	-	8.90	-				33.20
Rice husk ash	-	-	-	-	-	-	8.10	-				74.60

Table 2. Formulation of soil ameliorant based on humic and Si.

	Humic source		Si source		
Formula	Water hyacinth	Commercial humate	Rice husk ash	Rice husk biochar	Lime
	——— % ———		——— % ———		%
F0 (control)					100
F1		30	30		40
F2	30		30		40
F3	30			30	40
F4		30		30	40

Following the completion of soil ameliorant formulation, a comprehensive chemical composition analysis was conducted, encompassing pH, humic and fulvic acid levels, water content, total P, organic C, total N, cation exchange capacity (CEC), calcium oxide (CaO), magnesium oxide (MgO) and silicon dioxide (SiO_2). The pH was determined using a pH meter (410 A+, Thermo Orion, Waltham, Massachusetts, USA) humic and fulvic acid content were assessed using a UV-Vis spectrophotometer (Cary 50 Conc, Varian, Palo Alto, California, USA), heavy metals were analyzed with a UV-Vis spectrophotometer, total P was measured via a spectrophotometer using a 25% HCl extract, organic C was determined using the Black and Walkey method, total N was assessed using the Kjeldahl method, and cation exchange capacity (CEC) was measured using the 1 N NH_4OAC method. Total acidity was determined with 0.1 M $Ba(OH)_2$. For biochar and ash, SiO_2 analysis was conducted using hydrogen fluoride and H_2SO_4 extraction, while lime (Ca and Mg) analysis utilized a spectrophotometer. The results of the characterization of soil ameliorant materials are presented in Table 3. The formula used was 100% lime (F0), 30% commercial humate+30% rice husk ash+40% lime (F1), 30% water hyacinth humate+30% rice husk ash+40% lime (F2), 30% water hyacinth humate+30% rice husk biochar+40% lime (F3), 30% commercial humate+30% rice husk biochar+40% lime (F4).

Table 3. Formula characteristics of soil ameliorants. F0: 100% lime F1: 30% commercial humate+30% rice husk ash+40% lime; F2: 30% water hyacinth humate+30% rice husk ash+40% lime; F3: 30% water hyacinth humate+30% rice husk biochar+40% lime; F4: 30% commercial humate+30% rice husk biochar+40% lime. -: not analyzed. Source: Maftu'ah et al., 2023.

Characteristics	F0	F1	F2	F3	F4
pH	8.0	7.02	7.55	7.40	7.39
Humic acid, %	-	3.25	1.25	1.09	3.40
Fulvic acid, %	-	1.05	0.85	0.55	1.20
Total P, %	-	0.70	085	0.83	0.78
Organic C, %	-	20.15	18.50	28.30	25.60
Total N, %	-	1.55	1.24	1.63	1.46
SiO_2, %	2.85	30.50	33.15	23.90	20.50
Water content, %	1.79	8.20	9.25	9.60	7.55
CaO, %	29.40	-	-	-	-
MgO, %	18.75	-	-	-	-

The composition of the soil ameliorant formula significantly influences the characteristics of the resulting soil ameliorant. Lime (F1) boasts the highest pH level at 8, accompanied by CaO at 29.40%, MgO at 18.75%, and SiO_2 at 2.05%, while being devoid of humic substances. Formula 2 (F2) comprising 30% water hyacinth compost + 30% rice husk ash + 40% lime, exhibited the pH at 7.55, nearly identical to F3 at 7.40. Similarly, the total P content in F2 was 0.85%, slightly surpassing F3 at 0.83%. Notably, F2 also displayed the highest SiO_2 content at 33.15%, while F1 recorded 30.50%, and F3 and F4 had comparatively lower levels.

Soil characterization

The acid sulfate soil used in this study was sourced from typology B tidal swampland in Tanjung Harapan Village, Alalak District, Barito Kuala Regency, South Kalimantan. The initial soil characterization involved determining the pyrite content through a 30% H_2O_2 oxidation spectrophotometer, measuring pH using a pH meter, assessing organic C using the Black and Walkey method, determining total N through the Kjeldahl method, measuring total P using a 25% HCl extraction spectrophotometer, evaluating available P using the Bray 2 method spectrophotometer, analyzing the content of Ca, Mg, and K through atomic absorption spectrophotometer (AAS) extraction NH_4OAc 1 N pH 7, determining Fe using AAS extraction NH_4OAc 1 N pH 4, measuring sulfate using a water extraction spectrophotometer at a 1:5 ratio, and assessing Al using the 1 N KCl titration method.

Laboratory experiment

The laboratory experiment took place in the Laboratory of the Indonesia Swampland Agricultural Research Institute, Banjarbaru, South Kalimantan. The experimental design used was a simple randomized block design, incorporating treatments F0, F1, F2, F3, and F4 (Table 2), along with a control treatment featuring no soil ameliorant. To ensure robust results, each treatment was replicated five times, resulting in a total of 30 incubation glasses (6 treatments × 5 replicates).

The acid sulfate soil used in this experiment had a water content ranging from 30% to 40%. Subsequently, 200 g soil were weighed and placed into an incubation glass. The total soil ameliorant dose applied was 2 t ha^{-1}, equivalent to 0.2 g cup^{-1} of incubation. The specific type and quantity of soil ameliorant were determined based on the treatment, and after weighing, the ameliorant was placed in plastic and assigned a treatment code. The prepared ameliorant, corresponding to each treatment, was then introduced into the incubation glass containing the soil and assigned a treatment code. The mixture was stirred until it achieved a smooth consistency. The experimental conditions in the pots were maintained in a flooded or reductive state. Periodic soil observations were conducted at 2 and 4 wk after incubation. Soil samples were taken from each incubation glass, and the soil properties were analyzed for pH, redox potential (Eh), available P, Fe, and sulfate. Soil pH was measured using a pH meter, Eh was determined using an Eh meter, and available P, Fe, and sulfate were quantified using a spectrophotometer.

Greenhouse experiment

The experiment was carried out in the Greenhouse of the Indonesia Swampland Agricultural Research Institute in Banjarbaru, South Kalimantan, Indonesia. The chosen experimental design was a factorial randomized block design, incorporating two factors: Factor 1, soil ameliorant formula (F0, F1, F2, F3, F4) (Table 2); and Factor 2, dosage of soil ameliorant control without soil ameliorant (D0), 1, 2, and 4 t ha^{-1} (D1, D2, D3, respectively). This design resulted in 20 treatment combinations, comprising five ameliorant formulas each at four dose levels. To ensure robust results, each treatment was replicated three times, utilizing a total of 60 pots in the experiment.

The rice cultivar selected for this experiment was Inpara 8. Acid sulfate soil, obtained from the field, was added to each experimental pot at a rate of 5 kg pot^{-1}, specific to the treatment. Subsequently, the designated soil ameliorant treatment was applied to each pot according to the respective treatment. Rice seeds were planted 2 wk after the application of soil ameliorants. After 3 wk of sowing, the healthiest rice seeds were chosen and transplanted into each pot, with two seeds per pot. The pots were then saturated with water to a level 3 cm above the soil surface. Initial fertilization occurred when the plants were 3 d-old, incorporating basal fertilizer at 100 kg ha^{-1} urea and 400 kg ha^{-1} NPK, or the equivalent of 0.25 g urea pot^{-1} and 1.0 g NPK pot^{-1}. Subsequent fertilizations were performed at 27 and 35 d after planting (DAP) with an NPK dose of 200 kg ha^{-1}, equivalent to 0.8 g pot^{-1}.

Plant maintenance was carried out by maintaining the saturation level in the pot, ensuring a daily supply of ion-free water proportional to the decrease in water level. Additionally, every 2 wk, the water in the pot was replaced with fresh ion-free water. As a preventive measure, pest control was implemented through the intermittent application of insecticides and fungicides every 2 wk.

Soil sampling was carried out at the end of the vegetative period. During this time, various soil parameters, such as pH (H_2O), available phosphate (Bray 1), and Fe^{2+}, were regularly monitored. Plant height and number of tillers were measured at 2, 4, and 6 wk after planting (WAP). Destructive samples were taken at the end of the vegetative period to analyze dry weight, as well as Fe content in the roots and leaves of rice plants. Upon reaching the harvest stage, yield components and yield of the rice plant were calculated. These components encompass the number of rice grains per panicle, weight of 100 g rice grains, and rice yield per pot.

Data analysis

The obtained data was subjected to analysis using a variance F test at a significance level of 5%. If a significant difference was observed, further analysis was conducted using Duncan's multiple range test at a 5% significance level.

RESULTS AND DISCUSSION

Soil characteristics

The results of the initial soil analysis used for research are shown in Table 4. The soil pH values, both in H_2O and KCl, indicate a very acid classification. This acidity is further supported by notably high exchangeable Al and H values, which contribute to the overall soil acidity. The organic C and total N values fall within a moderate range, while total P is characterized as very low and available P as moderate. Total K_2O is assessed as low, and exchangeable K is classified as very low. In acid sulfate soils, the predominant challenge lies in the elevated concentrations of Fe and sulfate, coupled with low availability of P and K. Developing acid sulfate land for rice cultivation poses complications due to the presence of a pyrite layer, which, if oxidized, leads to heightened soil acidity (Kochian et al., 2004). Additionally, acid sulfate soils exhibit deficiencies in both macro and micronutrients (Panhwar et al., 2016). The elevated levels of Fe can induce toxicity in rice, potentially causing yield reductions ranging from 30% to 100%, depending on factors such as variety resistance, toxicity intensity, and soil fertility status (Majerus et al., 2007; Müller et al., 2015).

Pyrite is one of the primary contributors to acidity in acid sulfate soils (Jayalath et al., 2016). The oxidation of 1 mole of pyrite yields 4 moles of sulfuric acid (Shamshuddin et al., 2013). Various factors influence the level of soil acidity change resulting from pyrite oxidation, including the availability of oxygen and ferric ions (Fe^{3+}), decomposable organic matter, initial soil pH value, availability of basic cations, pyrite content, and soil hydrological conditions. Notably, soil moisture or hydrological conditions emerge as the primary determinants of acidity in acid sulfate soils (Karimian et al., 2017).

Table 4. Characteristics of acid sulfate soil used in this study.

Soil characteristics	Value	Criteria
pH H_2O	3.84	Very acid
pH KCl	3.68	Very acid
Electrical conductivity, µS cm^{-1}	200.00	moderate
Organick C, %	3.37	moderate
Total N, %	0.25	moderate
Available P, mg kg^{-1}	10.35	moderate
Total P, mg 100 g^{-1}	2.36	Very low
Total K_2O, mg 100 g^{-1}	10.63	Low
Exchangeable K, $cmol_{(+)}$ kg^{-1}	0.08	Very low
Exchangeable Na, $cmol_{(+)}$ kg^{-1}	0.74	High
Exchangeable Ca, $cmol_{(+)}$ kg^{-1}	1.12	Very low
Exchangeable Mg, $cmol_{(+)}$ kg^{-1}	1.97	moderate
Cation exchange capacity, $cmol_{(+)}$ kg^{-1}	23.85	moderate
Exchangeable Al, $cmol_{(+)}$ kg^{-1}	4.10	Very high
Exchangeable H, $cmol_{(+)}$ kg^{-1}	4.22	Very high
Exchangeable Fe, mg kg^{-1}	1704.68	Very high
SO_4^{2-}, mg kg^{-1}	245.19	Very high
FeS_2, %	0.93	High

Effect of Si-humate in improving acid sulfate soil properties in incubation experiments

The results of the incubation experiment showed that F4 formula (30% commercial humic material + 30% rice husk biochar + 40% lime) exhibited the highest pH value in the second week, while the F3 formula (30% water hyacinth humic +30% rice husk biochar + 40% lime) demonstrated the highest pH at 4 wk. All formulations of soil ameliorant had a higher effect on elevating the pH of H_2O in acid sulfate soils compared to the use of 100% lime at the same dose (F0). The application of soil ameliorants increased the pH of H_2O from 3.18 to 3.63 and the pH of KCl from 2.75 to 3.0 (Figure 1).

Upon analyzing the soil's ameliorant characteristics, it is evident that formula F3 exhibits a higher pH value compared to F4 (Table 1). Notably, the F3 formula demonstrated the highest electrical conductivity (EC) values at both the 2-wk and 4-wk observations after incubation, namely 0.710 and 0.870 mS cm^{-1}, respectively. These findings indicate that F3 effectively enhances the concentration of dissolved ions, particularly base ions, in the soil solution.

The formula that increased the highest P nutrient availability at the 4 wk observation after incubation was F3 (30% water hyacinth humic + 30% rice husk ash + 40% lime). There was an increase in P availability for all treatments, with the F3 treatment displaying the highest P concentration at 30.16 mg kg^{-1}. Additionally, F3 demonstrated the capability to decrease the Fe^{2+} concentration from 690 mg kg^{-1} (control) to 270 mg kg^{-1}, as well as lower the SO_4^{2-} concentration from 5350 mg kg^{-1} (control) to 2650 mg kg^{-1} (Figure 1). The synergistic combination of humate from water hyacinth compost and silica from rice husk biochar can reduce Fe concentrations in acid sulfate soil (Maftu'ah et al., 2023). Humic materials, through a chelation mechanism, can decrease phosphate fixation by Fe and Al, making P more accessible to plants. Additionally, the presence of silica anions reacts with metal cations, including Al and Fe, facilitating the release of phosphate ions and increasing their availability to plants (Siregar and Annisa, 2020).

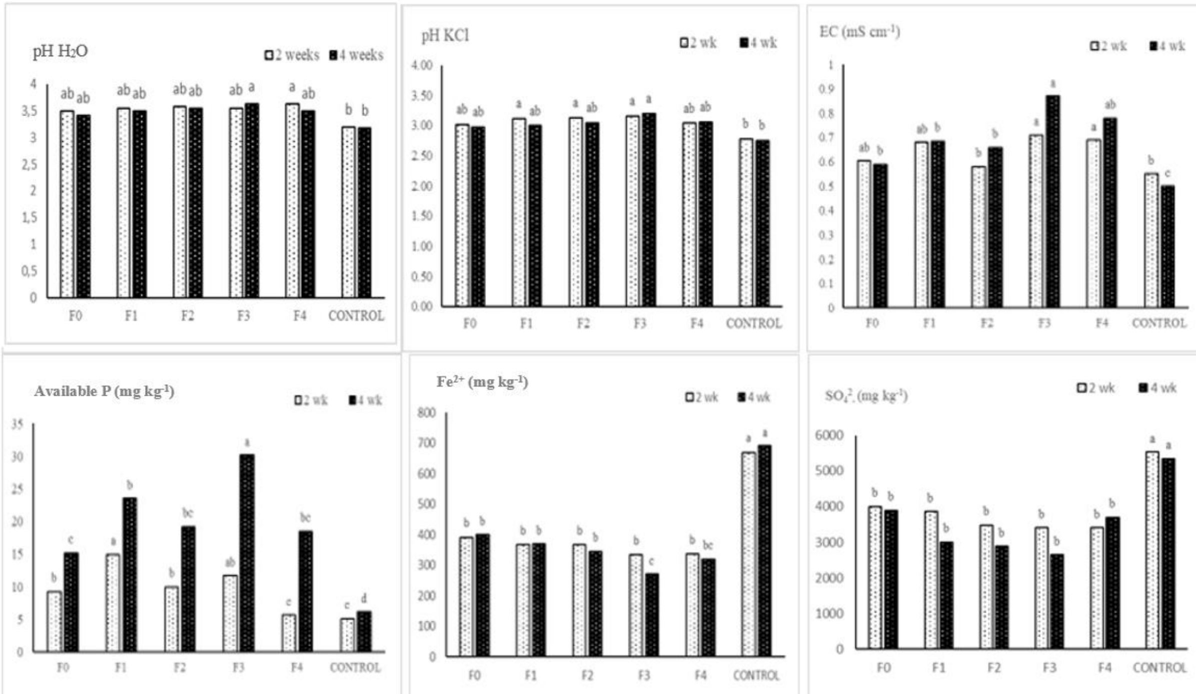

Figure 1. Effect of the type of soil ameliorant formula on soil chemical properties in laboratory incubation experiments. F0: 100% lime; F1: 30% commercial humate+30% rice husk ash+40% lime; F2: 30% water hyacinth humate+30% rice husk ash+40% lime; F3: 30% water hyacinth humate+30% rice husk biochar+40% lime; F4: 30% commercial humate+30% rice husk biochar+40% lime. Different letters indicate significantly different mean Duncan's multiple range test $p < 0.05$.

Silica exerts a beneficial influence by mitigating Al and Fe toxicity in the soil, diminishing the Fe content on the surface of rice roots, and reducing Fe uptake in lowland rice plants through an increase of oxidative strength in the roots. In swamplands, silica demonstrates the potential to diminish the solubility of heavy metals in the soil. The application of Si in rice cultivation can increase grain yield by 50.8% (Siregar and Annisa, 2020). The provision of Si in the soil enhances the tolerance of rice plants to various biotic stresses (Perez et al., 2014; Debona et al., 2017) and abiotic stresses, including toxic metals (Song et al., 2014; Abbas et al., 2015; Coskun et al., 2019). Silicon, as an element, plays a pivotal role in alleviating the impacts of toxicity on rice plants by reducing Fe concentrations in leaf and root tissues while concurrently enhancing the activity of the antioxidant system (Chalmardi et al., 2014; Dufey et al., 2014).

Humates play an important role in increasing the availability of both macro and micronutrients, thereby contributing to increased crop yields (Rahi et al., 2021). The humic and fulvic acids within humates can contribute to the negative charge to the soil, functioning as organic soil colloids. This negative charge is sourced from carboxyl and phenolic groups, which play a role in chelating reactions, particularly with toxic elements like Al and Fe. Humic acid, specifically, proves effective in various aspects of plant development, including root growth, crop yield improvement, stimulation of soil microorganisms, enhancement of soil water retention, promotion of seed germination, and augmentation of nutrient availability, such as N, P, K, Fe, and Zn. Additionally, it contributes to soil structure improvement, prevents salt accumulation, and facilitates soil aeration (Fahramand et al., 2014).

Effect of Si-humate soil ameliorant and dosage on chemical properties of acid sulfate soil in greenhouse experiments

The Si-humate soil ameliorant and its dosage significantly influenced soil pH, available P, and exchangeable Fe in greenhouse experiments (Figure 2). Treatments F2D2, F2D3, F1D2, F1D3, and F0D3 exhibited the highest soil pH values. Treatment F3D2 demonstrated the highest P availability at 21.25 mg kg^{-1}, representing a 1.75-fold increase compared to the soil without amendment. These findings align with incubation experiments where the F3 treatment consistently showed the highest P availability (Figure 1). In acid sulfate soils, P availability is typically low due to its adsorption by Fe (Gypser et al., 2021). The application of biochar can increase P availability in acid-sulfate soils (Phuong et al., 2020).

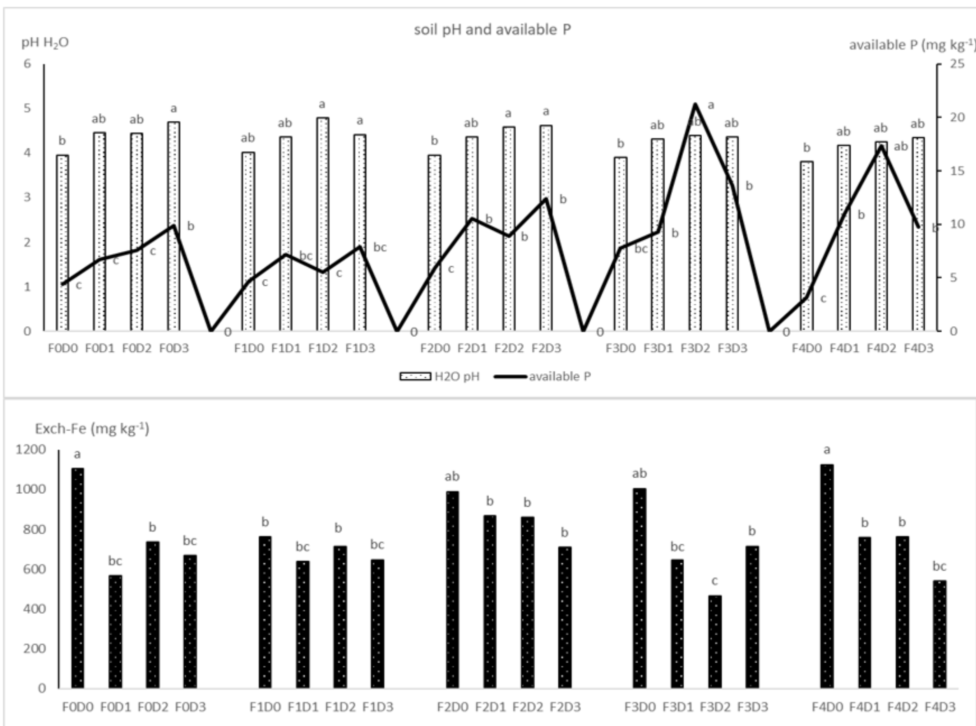

Figure 2. Effect of Si-humate on pH, available P and exchangeable Fe (Exch-Fe) in soil. F0: 100% lime; F1: 30% commercial humate+30% rice husk ash+40% lime; F2: 30% water hyacinth humate+30% rice husk ash+40% lime; F3: 30% water hyacinth humate+30% rice husk biochar+40% lime; F4: 30% commercial humate+30% rice husk biochar+40% lime. D0: 0 t ha^{-1}; D1: 1 t ha^{-1}; D2: 2 t ha^{-1}; D3: 4 t ha^{-1}. Different letters indicate significantly different mean Duncan's multiple range test $p < 0.05$.

In this pot experiment, the highest concentration of exchangeable Fe in the soil was observed in all control treatments, particularly in the F0D0 and F4D0 treatments. The application of soil ameliorants demonstrated a notable reduction in Fe concentrations ranging from 6.7% to 53% compared to the untreated soil. Among the treatments, the F3D2 treatment exhibited the lowest Fe concentration, measuring 467 ppm and effectively suppressing 53% of the control (1005 ppm). The Si-humate formula played a pivotal role in diminishing Fe concentrations and releasing various nutrients, especially P, making them accessible to plants. The presence of Si in the formula contributed to reducing the adverse effects on rice plants by lowering the concentration of Fe in both leaf and root tissues. Additionally, it enhanced the activity of the antioxidant system, improved plant growth, and reinforced the strength and straightness of leaves, thereby preventing mutual shading among leaves.

Effect of Si-humic soil ameliorant and dosage on rice growth

The soil ameliorant formula and its dosage demonstrated a significant interaction with both plant height and number of tillers (Table 5). Notably, the highest plant height at 2, 4, and 6 wk after planting (WAP) was observed in the F3 treatment at a dose of 1 t ha^{-1}, while the greatest number of tillers was recorded for the F3 treatment at a dose of 4 t ha^{-1}. This trend can be attributed to the concentration of available P in the soil, as illustrated in Figures 1 and 2, where the F3 treatment exhibited the highest available P concentration. The F3 soil ameliorant is composed of humic material from water hyacinth compost, Si from rice husk biochar, and agricultural lime. This formula has proven to be more effective in enhancing P availability in acid sulfate soils. Remarkably, rice husk biochar surpasses rice husk ash in improving various chemical properties of acid sulfate soil, including pH, organic C, available P, cation exchange capacity (CEC), exchangeable K, exchangeable Mg, exchangeable Na, and the reduction of Al and Fe (Masulili et al., 2010).

Table 5. Effect of type and dose of soil ameliorant formula on rice growth. F0: 100% lime; F1: 30% commercial humate+30% rice husk ash+40% lime; F2: 30% water hyacinth humate+30% rice husk ash+40% lime; F3: 30% water hyacinth humate+30% rice husk biochar+40% lime; F4: 30% commercial humate+30% rice husk biochar+40% lime. D0: 0 t ha^{-1}; D1: 1 t ha^{-1}; D2: 2 t ha^{-1}; D3: 4 t ha^{-1}. Values assigned the same letter in a column are considered statistically indistinct based on the Duncan's multiple range test ($p < 0.05$).

Treatment		Plant height (cm)			Tiller number		
		wk after planting			wk after planting		
Formula	Dose	2	4	6	2	4	6
F0	D0	44.67^{ab}	75.00^{bc}	86.67^{c}	2.33	6.00^{b}	10.33^{b}
	D1	46.17^{ab}	80.33^{b}	93.33^{bc}	3.00	6.67^{ab}	12.67^{ab}
	D2	44.17^{ab}	80.00^{b}	94.67^{ab}	2.33	6.33^{ab}	13.33^{ab}
	D3	47.67^{ab}	80.00^{b}	96.00^{ab}	2.67	6.33^{ab}	10.00^{b}
F1	D0	43.00^{b}	75.40^{bc}	85.00^{c}	2.33	6.00^{b}	9.00^{b}
	D1	48.50^{ab}	80.67^{b}	95.00^{ab}	2.67	6.00^{b}	10.00^{b}
	D2	49.33^{a}	82.17^{ab}	93.00^{b}	3.00	6.33^{ab}	10.00^{b}
	D3	44.83^{ab}	77.00^{b}	93.33^{ab}	2.33	4.67^{b}	8.67^{b}
F2	D0	43.33^{b}	75.18^{bc}	91.67^{b}	2.33	6.00^{b}	8.67^{b}
	D1	48.33^{ab}	84.33^{ab}	93.17^{b}	2.00	6.00^{b}	12.67^{ab}
	D2	49.50^{a}	80.00^{b}	96.33^{ab}	2.67	6.00^{b}	9.33^{b}
	D3	51.33^{a}	84.67^{ab}	94.83^{ab}	2.67	6.33^{ab}	10.67^{b}
F3	D0	41.33^{b}	71.67^{c}	93.33^{b}	2.33	6.00^{b}	9.00^{b}
	D1	46.33^{ab}	83.67^{ab}	100.33^{a}	2.67	5.33^{b}	9.33^{b}
	D2	53.33^{a}	85.50^{ab}	98.00^{ab}	3.00	7.67^{a}	12.33^{ab}
	D3	54.00^{a}	90.67^{a}	100.00^{a}	4.00	8.6 ^{a}	15.33^{a}
F4	D0	44.67^{b}	71.60^{c}	89.00^{c}	2.67	5.33^{b}	7.67^{b}
	D1	45.50^{ab}	79.33^{bc}	98.67^{ab}	2.00	6.00^{b}	10.00^{b}
	D2	45.50^{ab}	80.67^{bc}	95.17^{ab}	2.33	5.33^{b}	11.67^{ab}
	D3	45.50^{ab}	78.00^{bc}	94.83^{ab}	2.33	5.00^{b}	10.33^{b}

The plant's dry weight at the end of the vegetative stage serves as a reliable indicator of overall plant growth. The roots and shoots' weight in rice plants demonstrated significant variation influenced by the Si-humate soil amendment formula and dosage (Figure 3). Notably, the F3D3 treatment exhibited the highest root dry weight at 25.4 g pot^{-1}, while the highest shoot dry weight 35.8 g pot^{-1} was also observed in the F3D3 treatment. This result did not show a significant difference from F3D2 and F2D1. The heightened soil-available P content in the F3 formula treatment plays a multifaceted role in the plant development process. This includes contributions to seed germination, formation of seeds, roots, shoots, flowers, and seed development, as well as supporting photosynthesis, respiration, and N fixation (Malhotra et al., 2018). On acid sulfate land, P often acts as a limiting factor for plant growth (Fahmi et al., 2023). Providing P fertilizer not only supplies essential P to plants but also aids in reducing exchangeable Al and Fe levels, thereby increasing rice growth on acid sulfate land (Nguyen et al., 2017).

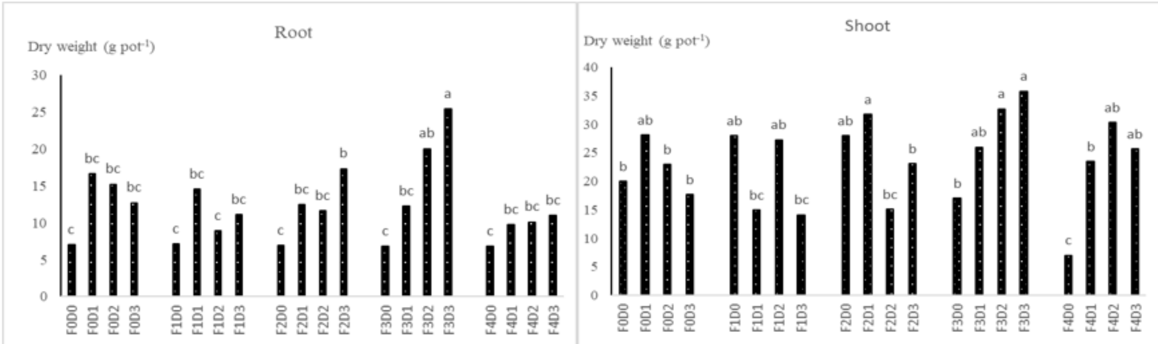

Figure 3. Effect of Si-humate on dry weight of rice plants. F0: 100% lime; F1: 30% commercial humate+30% rice husk ash+40% lime; F2: 30% water hyacinth humate+30% rice husk ash+40% lime; F3: 30% water hyacinth humate+30% rice husk biochar+40% lime; F4: 30% commercial humate+30% rice husk biochar+40% lime. D0: 0 t ha^{-1}; D1: 1 t ha^{-1}; D2: 2 t ha^{-1}; D3: 4 t ha^{-1}. Different letters indicate significantly different mean Duncan's multiple range test $p < 0.05$.

Effect of Si-humic soil ameliorant and dosage on Fe levels in rice plant tissue

The prevalence of Fe in acid sulfate soil poses challenges for rice plants, particularly in flooded conditions. Elevated Fe concentrations can lead to toxicity in rice plants, with the critical threshold for Fe levels in plant leaf tissue varying between 0.03% and 0.20%. However, these thresholds depend on factors such as the plant's condition, age, and specific soil conditions. The control without soil ameliorant exhibited higher Fe concentrations in both roots and shoots compared to the Si-humate soil amendment treatment. The research findings indicate that the use of soil ameliorants effectively decreased Fe levels in both root and shoot tissues. The F3D2 treatment demonstrated the lowest Fe concentration in plant roots, and similarly, in plant shoots, it was also lowest in F3D2, with nonsignificant difference from F0D2 and F3D3 (Figure 4). Specifically, the application of the F2D2 soil ameliorant led to a substantial reduction in Fe levels, decreasing from 7.22% to 1.20% in plant root tissue and from 0.29% to 0.21% in plant shoots.

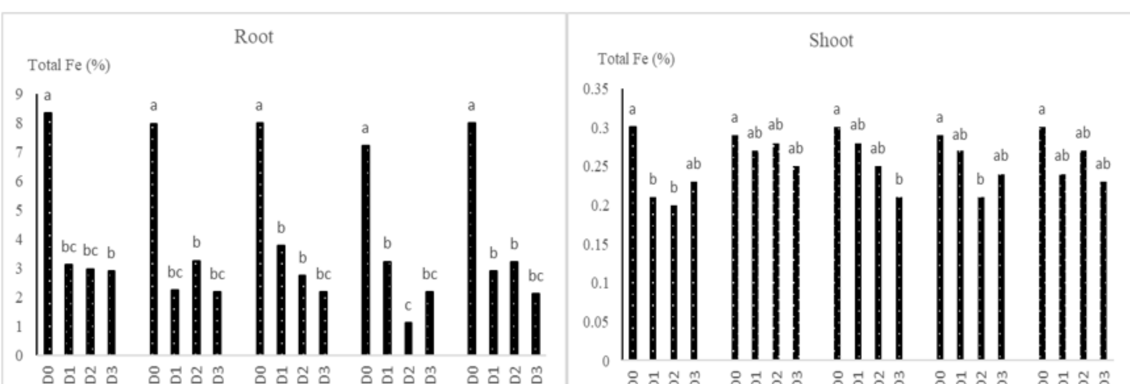

Figure 4. Effect of Si-humate on Fe concentration in rice plant tissue. F0: 100% lime; F1: 30% commercial humate+30% rice husk ash+40% lime; F2: 30% water hyacinth humate+30% rice husk ash+40% lime; F3: 30% water hyacinth humate+30% rice husk biochar+40% lime; F4: 30% commercial humate+30% rice husk biochar+40% lime. D0: 0 t ha^{-1}; D1: 1 t ha^{-1}; D2: 2 t ha^{-1}; D3: 4 t ha^{-1}. Different letters indicate significantly different mean Duncan's multiple range test $p < 0.05$.

The research findings reveal a high Fe concentration in the root tissue, aligning with the elevated Fe levels observed in the soil (Figures 1 and 2). As supported by previous research (Noor et al., 2012), there exists a positive correlation between the Fe content in the soil solution and the Fe content in plant tissue. Rice plants have a mechanism to cope with heightened Fe concentrations in the soil, wherein they exclude Fe^{2+} at the root surface, preventing its entry into leaf tissue and storing the Fe in the root cortex. Furthermore, amelioration practices in acid sulfate soils prove effective in controlling Fe concentrations, suppressing Fe uptake by plants, and enhancing the overall growth and yield of rice plants (Khairullah et al., 2021).

The growth and yield of rice in acid sulfate soils are significantly influenced by Fe toxicity. Yield reductions attributed to Fe toxicity range from 30% to 100%, contingent upon factors such as variety tolerance, intensity of exposure to toxicity, and fertility status of the soil (Majerus et al., 2007). Leaf bronzing, a recognized symptom of Fe toxicity, correlates with elevated Fe levels in plant shoots. The absorption of ferrous Fe by plants and its accumulation in the leaves lead to noticeable color changes in the leaves (Majerus et al., 2007). The Fe toxicity manifests in various symptoms, including decreased plant height, reduced tillering, and diminished chlorophyll content (Fageria et al., 2008). Plants affected by Fe poisoning exhibit sparse, rough, short, and dark brown roots. As Fe toxicity stress intensifies, plant leaves shift to a purplish-brown color, followed by leaf drying, resembling a burned appearance (Sahrawat, 2004).

Effect of Si-humic soil ameliorant and dosage on rice yield

The Si-humate soil ameliorant and dosage did not have a significant impact on panicle length and the number of panicles, but notable differences were observed in the weight of 100 g grain and the overall weight per pot. The highest dry grain weight was achieved with the F3 soil ameliorant at doses of 4 and 2 t ha^{-1} (Figure 5). The effectiveness of the F3 formula in increasing P availability and decreasing Fe in acid-sulfate soils is evident in Figure 1. The application of P and silica fertilizers noticeably affects rice yield (Wang et al., 2019). Phosphorus plays a pivotal role in various plant processes, including seed germination, seed and plant development, photosynthesis, respiration, and N fixation (Malhotra et al., 2018). Phosphorus availability is generally low on acid sulfate land in tidal swamps, influenced by the presence of Fe ions (Fahmi et al., 2023). The application of phosphate fertilizer serves to supply P to plants and aids in diminishing exchangeable levels of Al and Fe, consequently enhancing rice growth in acidic soils (Nguyen et al., 2017).

In the greenhouse experiment, the correlation analysis revealed a significant positive association between yield components and rice yield with soil pH. The correlation coefficients (r) for each variable in relation to soil pH were as follows: Number of panicles ($r = +0.40^*$), number of grains per pot ($r = +0.35^*$), number of filled grains per pot ($r = +0.47^{**}$), and weight of grain per pot ($r = +0.43^*$). However, nonsignificant correlation was observed between these crop yield components and the levels of available P and exchangeable Fe. Soil samples were collected at the end of the vegetative period to consider nutrient absorption by plants. Consequently, the remaining P in the soil does not directly reflect plant outcomes.

The research findings indicate that the Si-humate F3 formula at a dosage of 4 t ha^{-1} (F3D3) increased grain yield by 4.22 g pot^{-1}, while F3D2 raised it by 3.74 g pot^{-1} compared to the control-without soil ameliorant. This improvement was equivalent to 0.91 and 0.66 g pot^{-1} when compared with the application of 100% lime at 4 and 2 t ha^{-1}, respectively. The application of Si in rice cultivation has been shown to enhance grain yield by 50.8% (Siregar and Annisa, 2020). Silica, derived from rice husks, demonstrates the potential to reduce the solubility of heavy metals in swampy soil. Silica serves as an adsorbent and selective agent for adsorbing metal ions and is widely used for this purpose. Introducing Si elements into the soil enhances the tolerance of rice plants to various biotic stresses (Debona et al., 2017) and abiotic stresses, including toxic metals (Song et al., 2014; Abbas et al., 2015; Sanglard et al., 2016; Coskun et al., 2019). The Si element can reduce the impact of poisoning on rice plants by reducing Fe concentrations in leaf and root tissues and enhancing the activity of the antioxidant system (Chalmardi et al., 2014; Dufey et al., 2014).

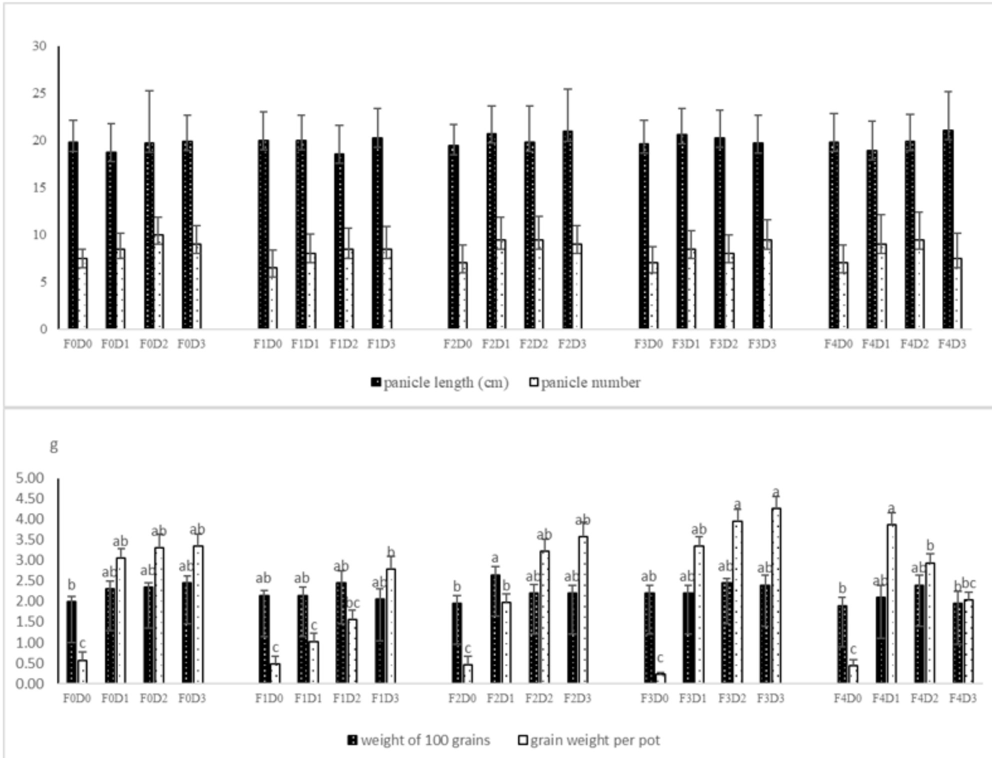

Figure 5. Effect of Si-humic soil ameliorant on yield components and rice yield. F0: 100% lime; F1: 30% commercial humate+30% rice husk ash+40% lime; F2: 30% water hyacinth humate+30% rice husk ash+40% lime; F3: 30% water hyacinth humate+30% rice husk biochar+40% lime; F4: 30% commercial humate+30% rice husk biochar+40% lime. D0: 0 t ha^{-1}; D1: 1 t ha^{-1}; D2: 2 t ha^{-1}; D3: 4 t ha^{-1}. Different letters indicate significantly different mean Duncan's multiple range test $p < 0.05$.

CONCLUSIONS

The Si-humic soil ameliorant effectively enhances soil pH, increases available P, and mitigates the solubility of Fe and sulfate in acid sulfate soils. The Si-humate F3 ameliorant, composed of 30% humate from water hyacinth compost, 30% rice husk biochar, and 40% lime, demonstrates the capability to promote plant growth. This includes improvements in plant height, the number of tillers, plant dry weight, a reduction in Fe toxicity, and an increase in rice yields. Specifically, the F3 Si-humate formula at a dosage of 4 t ha^{-1} increased grain yield by 4.22 g pot^{-1}, while F3 at 2 t ha^{-1} raised it by 3.74 g pot^{-1} compared to the control without soil ameliorant. This improvement was equivalent to 0.91 and 0.66 g pot^{-1} when compared with the use of 100% lime at 4 and 2 t ha^{-1}, respectively. The application of Si-humate not only enhances pH, available P, reduces Fe toxicity, and boosts rice yields but also diminishes the reliance on lime, offering potential benefits for maintaining soil health.

Author contributions

Conceptualization: E.M., Y.S., M.M. Methodology: E.M., M.S., R.D.N. Software: K.N., V.K., P.H.M. Validation: E.M., M.M. Formal analysis: E.M., M.M. Investigation: M.M., M.S., S.A., A.H., Y.L., K.A., M.G., N.W. Resources: A.H., R.DN., P.H.A. Data curation: K.N., M.S., R.A. Writing-original draft: E.M., Y.S., M.M., M.S., K.A. Writing-review & editing: E.M., M.M., Y.S., M.G. Visualization: N.W., A.F., V.K. Supervision: K.A., M.M., M.S. Project administration: R.A., K.N. Funding acquisition E.M., M.S. All co-authors reviewed the final version and approved the manuscript before submission.

References

Abbas, T., Balal, R.M., Shahid, M.A., Pervez, M.A., Ayyub, C.M., Aqueel, M.A., et al. 2015. Silicon-induced alleviation of NaCl toxicity in okra (*Abelmoschus esculentus*) is associated with enhanced photosynthesis, osmoprotectants and antioxidant metabolism. Acta Physiologiae Plantarum 37:5-15. doi:10.1007/s11738-014-1768-5.

Bourbonniere, R.A., Creed, I.F. 2006. Biodegradability of dissolved organic matter extracted from a chronosequence of forest-floor materials. Journal of Plant Nutrition and Soil Science 169:101-107. doi:10.1002/jpln.200521721.

Chalmardi, Z.K., Abdolzadeh, A., Sadeghipour, H.R. 2014. Silicon nutrition potentiates the antioxidant metabolism of rice plants under iron toxicity. Acta Physiologiae Plantarum 36:493-502. doi:10.1007/s11738-013-1430-7.

Coskun, D., Deshmukh, R., Sonah, H., Menzies, J.G., Reynolds, O., Ma, J.F., et al. 2019. The controversies of silicon's role in plant biology. New Phytologist 221:67-85. doi:10.1111/nph.15343.

Debona, D., Rodrigues, F.A., Datnoff, L.E. 2017. Silicon's role in abiotic and biotic plant stresses. Annual Review of Phytopathology 55:85-107. doi:10.1146/annurev-phyto-080516-035312.

Dufey, I., Gheysens, S., Ingabire, A., Lutts, S., Bertin, P. 2014. Silicon application in cultivated rice (*Oryza sativa* L. and *Oryza glaberrima* Steud) alleviates iron toxicity symptoms through the reduction in iron concentration in the leaf tissue. Journal of Agronomy and Crop Science 200(2):132-142. doi:10.1111/jac.12046.

Fageria, N.K., Santos, A.B., Barbosa F.M.P., Guimarães, C.M. 2008. Iron toxicity in lowland rice. Journal of Plant Nutrition 31:1676-1697. doi:10.1080/01904160802244902.

Fahmi, A., Hairani, A., Alwi, M., Nurzakiah, S. 2023. Fe-P pools as phosphorus source for rice in acid sulfate soils. Chilean Journal of Agricultural Research 83:626-634. doi:10.4067/s0718-58392023000500626.

Fahramand, M., Moradi, H., Noori, M., Sobhkhizi, A., Adibian, M., Abdollahi, S., et al. 2014. Influence of humic acid on increase yield of plants and soil properties. International Journal of Farming and Allied Sciences 3(3):339-341.

Gypser, S., Schütze, E., Freese, D. 2021. Single and binary Fe- and Al-hydroxides affect potential phosphorus mobilization and transfer from pools of different availability. Soil Systems 5:33. doi:10.3390/soilsystems5020033.

Jayalath, N., Mosley, L.M., Fitzpatrick, R.W., Marschner, P. 2016. Addition of organic matter influences pH changes in reduced and oxidized acid sulfate soils. Geoderma 262:125-132. doi:10.1016/j.geoderma.2015.08.012.

Karimian, N., Johnston, S.G., Burton, E.D. 2017. Antimony and arsenic behavior during Fe(II)-induced transformation of jarosite. Environmental Science & Technology 51(8):4259-4268. doi:10.1021/acs.est.6b05335.

Khairullah, I., Saleh, M., Alwi, M., Masganti, 2021. Increasing productivity of rice through iron toxicity control in acid sulfate soils of tidal swampland. IOP Conference Series: Earth and Environmental Science 648:012151. doi:10.1088/1755-1315/648/1/012151.

Kochian, L.V., Owen, A., Pineros, H.M.A. 2004. How do crop plants tolerate acid soils? Mechanisms of aluminum tolerance and phosphorous efficiency. Annual Review of Plant Biology 55:459-493. doi:10.1146/annurev.arplant.55.031903.141655.

Maftu'ah, E., Nurzakiah, S., Sulaeman, Y., Lestari, Y. 2023. Use of humic and silica materials as soil ameliorant to improve the chemical properties of acid sulphate soil. IOP Conference Series: Earth and Environmental Science 1162(1):012002. doi:10.1088/1755-1315/1162/1/012002.

Majerus, V., Bertin, P., Lutts, S. 2007. Effects of iron toxicity on osmotic potential, osmolytes and polyamines concentrations in the African rice (*Oryza glaberrima* Steud.) Plant Science 173:96-105. doi:10.1016/j.plantsci.2007.04.003.

Malhotra, H., Vandana, S., Sharma, Pandey, R. 2018. Phosphorus nutrition: Plant growth in response to deficiency and excess. In Hasanuzzaman, M., Fujita, M., Oku, H., Nahar, K., Hawrylak-Nowak, B. (eds.) Plant nutrients and abiotic stress tolerance. Springer Nature, Singapore. doi:10.1007/978-981-10-9044-8_7.

Masulili, A., Utomo, W.H., Syechfani, M.S. 2010. Rice husk biochar for rice based cropping system in acid soil. 1. The characteristics of rice husk biochar and its influence on the properties of acid sulfate soils and rice growth in West Kalimantan, Indonesia. Journal of Agricultural Science 2(1):39-47. doi:10.5539/jas.v2n1p39.

Müller, C., Kuki, K.N., Pinheiro, D.T., de Souza, L.R., Silva, A.I.S., Loureiro, M.E., et al. 2015. Differential physiological responses in rice upon exposure to excess distinct iron forms. Plant and Soil 391:123-138. doi:10.1007/s11104-015-2405-9.

Nguyen, D.N., Nguyen, T.T., Tran, Q.N., Macdonald, B., To, T.P., Tran, D.V. 2017. Soil and rice responses to phosphate fertilizer in two contrasting seasons on acid sulfate soil. Communications in Soil Science and Plant Analysis 48(6):615-623. doi:10.1080/00103624.2016.1253719.

Noor, A., Lubis, I., Ghulamahdi, M., Chozin, M.A., Anwar, K., Wirnas, D. 2012. Pengaruh Konsentrasi Besi dalam Larutan Hara terhadap Gejala Keracunan Besi dan Pertumbuhan Tanaman Padi. Jurnal Agronomi Indonesia 40(2):91-98. doi:10.24831/jai.v40i2.14311.

Nordmyr, M., Astrom, M., Peltola, P. 2008. Metal pollution of estuarine sediments caused byleaching of acid sulphate soils. Estuarine, Coastal and Shelf Science 76:141-152. doi:10.1016/j.ecss.2007.07.002.

Panhwar, Q.A., Naher, U.A., Radziah, O., Shamshuddin, J., Razi, I.M. 2014. Bio-fertilizer, ground magnesium limestone and basalt applications may improve chemical properties of Malaysian acid sulfate soils and rice growth. Pedosphere 24(6):827-835. doi:10.1016/S1002-0160(14)60070-9.

Panhwar, Q.A., Naher, U.A., Shamshuddin, J., Radziah, O., Hakeem, K.R. 2016. Management of acid sulfate soils for sustainable rice cultivation in Malaysia. p. 91-104. In Hakeem, K.R., Akhtar, J., Sabir, M. (eds.) Soil science: Agricultural and environmental prospectives. Springer International Publishing, Cham, Switzerland. doi:10.1007/978-3-319-34451-5_4.

Perez, C.E.A., Rodrigues, F.Á., Moreira, W.R., DaMatta, F.M. 2014. Leaf gas exchange and chlorophyll a fluorescence in wheat plants supplied with silicon and infected with *Pyricularia oryzae*. Phytopathology 104(2):143-9. doi:10.1094/PHYTO-06-13-0163-R.

Phuong, N.T.K., Khoi, C.M., Ritz, K., Linh, T.B., Minh, D.D., Duc, T.A., et al. 2020. Influence of rice husk biochar and compost amendments on salt contents and hydraulic properties of soil and rice yield in salt-affected fields. Agronomy 10:1101. doi:10.3390/agronomy10081101.

Rahi, A.A., Anjum, M.A., Mirza, J.I., Ali, S.A., Marfo, T.D., Fahad, S., et al. 2021. Yield enhancement and better micronutrients uptake in tomato fruit through potassium humate combined with micronutrients mixture. Agriculture 11:357. doi:10.3390/agriculture11040357.

Ritung, S., Suryani, E., Subardja, D., Sukarman, Nugroho, K., Suparto, et al. 2015. Sumberdaya Lahan pertanian Indonesia: Luas, penyebaran dan potensi ketersediaan. In Husen, E., Agus, F. Nursyamsi, D. (eds.) IAARD Press, Jakarta, Indonesia.

Sahrawat, K.L. 2004. Iron toxicity in wetland rice and the role of other nutrients. Journal of Plant Nutrition 27(8):1471-1504. doi:10.1081/PLN-200025869.

Sanglard, L.M.V.P., Detmann, K.C., Martins, S.C.V., Teixeira, R.A., Pereira, L.F., Sanglard, M.L., et al. 2016. The role of silicon in metabolic acclimation of rice plants challenged with arsenic. Environmental and Experimental Botany 123:22-36. doi:10.1016/j.envexpbot.2015.11.004.

Shamshuddin, J., Elisa, A.A., Shazana, R.S., Fauziah, C.I. 2013. Rice defense mechanisms against the presence of excess amount of Al^{3+} and Fe^{2+} in the water. Australian Journal of Crop Science 7(3):314-320. doi:10.1081/CSS-120027638.

Shamshuddin, J., Muhrizal, S., Fauziah, I., Ranst, E.V. 2004. A laboratory study on pyrite oxidation in acid sulfate soils. Communications in Soil Science and Plant Analysis 35(1&2):117-129. doi:10.1081/CSS-120027638.

Siregar, A.F., Annisa, W. 2020 Ameliorasi berbasis unsur hara silika di lahan rawa. Jurnal Sumberdaya Lahan 14 (1):37-47.

Song, A., Li, P., Fan, F., Li, Z., Liang, Y. 2014. The effect of silicon on photosynthesis and expression of its relevant genes in rice (*Oryza sativa* L.) under high-zinc stress. PLOS ONE 9(11):e113782. doi:10.1371/journal.pone.0113782.

Tregubova, P., Koptsik, G., Stepanov, A. 2019. Remediation of degraded soils: Effect of organic additives on soil properties and heavy metals' bioavailability. IOP Conference Series: Earth and Environmental Science 368(1):012054. doi:10.1088/1755-1315/368/1/012054.

Wang, L., Ashraf, U., Chang, C., Abrar, M., Cheng, X. 2019. Effects of silicon and phosphatic fertilization on rice yield and soil fertility. Journal of Soil Science and Plant Nutrition 20:557-565. doi:10.1007/s42729-019-00145-5.