Humate-Silica as an ameliorant to decrease Fe toxicity and increase rice yields on acid sulfate soils

Khairatun Napisah[1], and *Eni* Maftu'ah[1*]

[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

Abstract. Iron toxicity is a major problem in increasing rice production in acid-sulfate soils. Humate materials and Silica ions can interact with Fe ions to form chelates so that they can decrease Fe toxicity and increase rice yields. This research aimed to study the effect of humate-silica soil on decreasing Fe toxicity and increasing rice yields in acid-sulfate soils. The research employed a simple randomized block design incorporating treatments F0=100% lime, F1=30% humate manufacturer+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% humate manufacturer+30% rice husk biochar+40% lime, and control=without ameliorant. Each treatment was repeated 4 times. Observations of soil characteristics were carried out at the end vegetative stage including pH and Fe, while at the end of the research, observed including panicle length, 100g weight, and grain weight per pot. The findings indicated that F1 was able to increase pH and decrease Fe^{2+} concentration and wasn't significantly different from F3. Ameliorant F3 was able to decrease Fe toxicity and increase rice yields. The application of this formula resulted in a decrease in the usage of agricultural lime while enhancing rice productivity in tidal soil.

1 Introduction

The extent of tidal land in Indonesia encompasses approximately 8.92 million hectares [1]. The extent of acid sulfate land is on the rise, concurrent with the degradation of peatlands containing layers of sulfidic material beneath. Acid sulfate soil originates from parent material abundant in pyrite compounds (FeS_2). Upon oxidation, these compounds can acidify the soil, leading to Fe toxicity in rice plants [2]. The reaction of pyrite with oxygen, water, and Fe produces sulfuric acid which makes the soil have an extremely acidic pH and dissolved Fe (Fe^{2+}) is in toxic concentrations [3],

Iron (Fe) in acid sulfate soil that can cause poisoning in rice plants, especially in flooded conditions, is in the form of ferrous (Fe^{2+}). The levels of ferrous iron in acid sulfate fields exhibit considerable variation, ranging from 0.07 to 6600 ppm, contingent upon factors such

* Corresponding author: enim002@brin.go.id

as soil pH, organic matter, iron content, and reactivity [4]. Rice plants can already experience Fe toxicity if the concentration of Fe^{2+} in the water is 300 to 2,000 mg/kg [5]. The critical limit of iron content in plant leaf tissue ranges from 0.03 to 0.2% [6], however, it depends on the condition of the plant, the age of the plant, and soil conditions [7].

The detrimental effects of iron toxicity can lead to a decline in rice production ranging from 30% to 100%, influenced by factors such as varietal resistance, toxicity intensity, growth phase, and soil fertility status [8], 35.8 to 79.8% [9], and even up to 100% [10], of the potential yield depending on the variety [11]. Addressing iron toxicity in acid-sulfate land can be achieved by employing soil ameliorants. The use of 4 t/ha dolomite, for instance, can decrease iron levels from 189 mg/kg to 86 mg/kg [12]. The significant demand for lime to alleviate acidity is impractical, thus necessitating the development of ameliorant materials to minimize the reliance on agricultural lime.

Substitute materials for lime or options to decrease lime in acid sulfate soils include silica and humate materials. Silica plays a crucial role in mitigating the impacts of iron (Fe) and aluminum (Al) toxicity commonly found in acidic and poorly drained soils. Additionally, it enhances the availability of phosphorus (P) nutrients in the soil while reducing transpiration [13]. Silicon (Si) plays a crucial role in mitigating the uptake of iron (Fe) and aluminum (Al) under toxic conditions. Multiple research findings indicate that Si effectively reduces the levels of Al and Fe toxicity in the soil, decreases the surface Fe content on rice roots, and limits Fe uptake in lowland rice plants by enhancing the oxidative strength of the roots. The application of Si in rice cultivation has been shown to boost grain yield by 50.8% [14].

Humate materials exhibit the capability to interact with metal ions, including aluminum (Al) and iron (Fe), forming chelates. Findings from Ernawati's research [15] demonstrated that irrigating soil with 2.4 liters of peat water could decrease exchangeable aluminum (Al-exch) and raise the pH of acidic soil. Additionally, the application of humic compounds was shown to decrease Al-exch from 5.99 me/100g to 5.33 me/100g [16]. The utilization of humic materials in acid-sulfate soils plays a significant role due to its capacity to inhibit the solubility of iron (Fe).

The combined amendment of humate and silicon (Si) is anticipated to enhance its efficacy in mitigating iron (Fe) toxicity while promoting the growth and yield of rice in acid-sulfate terrain. This study aims to investigate the impact of Si-humate soil amendment on enhancing rice yields in acid sulfate soils.

2 Methodology

The investigation took place in the Greenhouse of the Indonesian Swampland Agriculture Standardization Institute in Banjarbaru, South Kalimantan, spanning from June to December 2022. This study focused on formulating various soil ameliorant materials derived from humate and silicon (Si), combined with lime.

The acid sulfate soil utilized in this research was sourced from Tanjung Harapan village, Alalak District, Barito Kuala Regency, South Kalimantan. The initial soil characteristics were recorded as pH-H2O 3.84, pH-KCl 3.68, and available phosphorus (P) at 10.35 ppm (Bray 2), Fe^{2+} 1704.58 ppm (AAS/NH_4OAc pH 4), and pyrite content 0.93% (Spectrophotometer/H_2O_2 oxidation 30%). The study employed a Randomized Block Design, encompassing the following treatments:

F0 = 100% lime
F1 = 30% humate manufacturer + 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% humate manufacturer + 30% rice husk biochar + 40% lime
Each treatment was replicated four times.

In the experiment, acid sulfate soil was extracted from the field layers at a depth of 0-50cm, ensuring it was in a moist and homogeneous state. Subsequently, 5 kg of soil per pot was utilized in the experimental setup.

The rice variety chosen for the study was Inpara 8. Seeds were sown, and rice seedlings were transplanted at three weeks of age. The transplantation of seedlings into the field occurred two weeks after the application of soil ameliorants.

Initial fertilization was performed three days after planting, employing 100 kg/ha of urea fertilizer and 400 kg/ha of Mutiara NPK, equivalent to 0.25 g of urea/pot and 1.0 g of NPK/pot. Subsequent fertilizations were conducted at 27 weeks and 35 weeks after planting (WAP) with an NPK dose of 200 kg/ha or 0.8 g per pot.

The care of the plants involved sustaining the water saturation level in the pots, providing ion-free water daily, and adjusting the quantity based on the decrease in the water level in each pot. Furthermore, pest management was implemented through regular spraying, alternating insecticides, and fungicides every two weeks to prevent attacks from pests.

After the vegetative phase, observations were conducted using destructive samples to analyze the dry weight and iron (Fe) content in both the roots and leaves (shoots) of the rice plants. Additionally, soil samples were collected for pH and Fe2+ analysis. Upon reaching the harvest stage, various yield components of the rice plant were calculated. These components included the number of rice grains per panicle, the weight of 100g of rice grains, and the overall rice yield per pot.

3 Results and discussion

3.1 The impact of humate-Si soil ameliorants on Fe concentration and soil pH

Soil ameliorants have an impact on the concentration of F^{e2+} and soil pH. Among the soil ameliorant formulas, F3, consisting of 30% water hyacinth humate, 30% rice husk biochar, and 40% lime, exhibits a superior ability to decrease Fe^{2+} levels in the soil compared to other formulations. However, in terms of soil pH, the F0 treatment demonstrates the highest value, and this is not significantly different from all treatments except the control (Fig. 1).

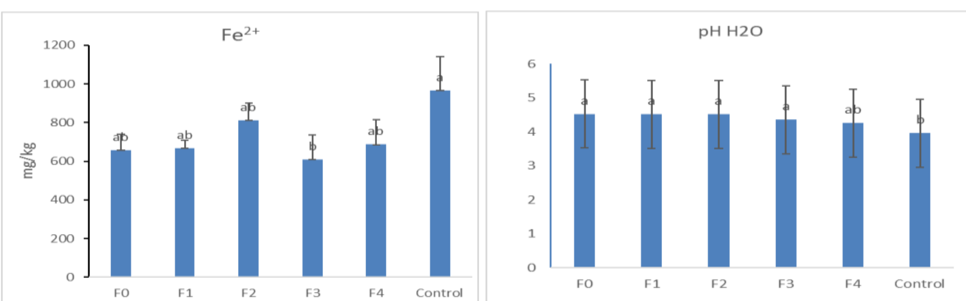

Fig. 1. The impact of the humate-Si soil ameliorant formula on Fe^{2+} concentration and soil pH.

The F3 humate soil ameliorant demonstrates the capability to mitigate Fe2+ in the soil solution by as much as 36%, reducing it from 965 ppm to 605 ppm. The inclusion of silicon (Si) from rice husk biochar and humate derived from water hyacinth compost contributes to a reduction in the need for lime. Moreover, biochar, besides serving as a Si source, plays a role in enhancing various soil properties, including cation exchange capacity (CEC), bulk density, and porosity, and promoting increased soil microbial activity.

Humic materials in acid sulfate soils play a crucial role in enhancing both the physical and chemical properties of the soil. Humate materials serve as organic ligands capable of chelating iron (Fe), leading to a reduction in its concentration in the soil solution. The presence of Fe^{2+} ions can influence the availability of phosphorus (P) in acid-sulfate soils, as they can form compounds like $FePO_4$, rendering P fertilization in the soil less effective. Therefore, the action of humate materials helps alleviate this issue by reducing Fe concentration and improving the overall soil conditions [17].

3.2 Impact of humate-Si soil ameliorant on Fe toxicity in paddy

The levels of iron (Fe) in both the roots and shoots of rice plants exhibited significant differences among treatments, as illustrated in Fig. 2. Notably, the concentration of Fe in plant roots was higher than in the shoots. Among the treatments, the F3 formula, specifically composed of 30% water hyacinth humate, 30% rice husk biochar, and 40% lime, displayed the lowest Fe levels in both the roots and shoots. For this formula, the Fe content was 2.2% in the roots and 0.24% in the shoots. Remarkably, F3 was able to elevate Fe levels in rice roots by up to 2.6 times and in the shoots by 22% when compared to the control group (without ameliorant).

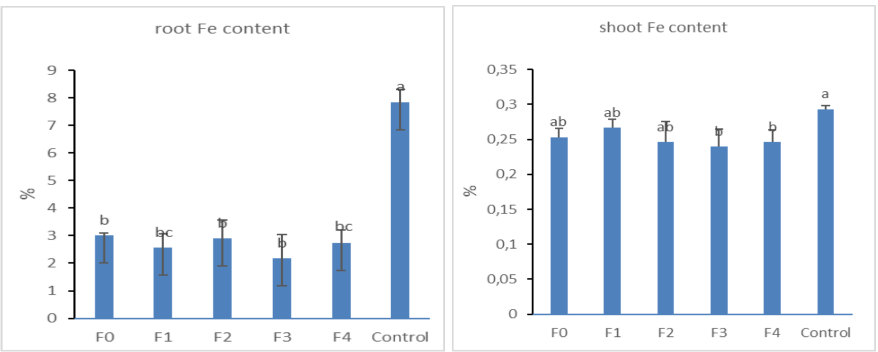

Fig. 2. The impact of the humate-Si soil ameliorant formula on iron (Fe) toxicity in shoot and root of paddy.

The observation that iron (Fe) levels in the roots are higher than in the shoots of rice plants suggests that Fe accumulation predominantly occurs in the roots, with only a limited amount of Fe being transported to the leaf tissue. The mechanism of Fe toxicity initiates with an augmented permeability of root cells to Fe^{2+} ions, coupled with an increase in the conversion of Fe^{3+} to Fe^{2+}. Consequently, there is uncontrolled flux of Fe^{2+} in the roots of rice plants [18]. Despite this, rice plants possess mechanisms to cope with environments characterized by excessive iron levels [19].

The use of soil amendment materials has the potential to decrease the concentration of iron (Fe) in the soil solution, thereby suppressing Fe uptake by rice plants. Specifically, soil amendment materials formulated with biochar, organic fertilizer, and lime demonstrate the capacity to lower the concentration of Fe^{2+} in acid-sulfate soil during planting. The reduction is substantial, decreasing from an initial concentration of 6400 ppm to a range of 1000-1500 ppm [20]. This highlights the effectiveness of these soil amendments in mitigating excessive Fe levels in the soil and promoting a more favorable environment for rice cultivation

Biochar serves as a source of silicon (Si), playing a vital role in inhibiting iron (Fe) solubility in acid-sulfate soil and curbing Fe uptake by rice plants. Si functions as a metal neutralizer by undergoing an immobilization process in the roots before being transported to the shoots. Additionally, Si enhances the volume of the aerenchyma, which refers to the air spaces in both the roots and shoots, facilitating oxygen transport to the roots. Moreover, Si can oxidize iron and manganese into less toxic forms [14]. The presence of Si can alleviate the adverse effects of toxicity on rice plants by reducing Fe concentrations in both leaf and root tissues while enhancing the activity of the antioxidant system [21, 22].

Humic acid plays a crucial role in chelating toxic ions, particularly iron (Fe) and aluminum (Al), contributing to the improvement of fertility in acid sulfate soils [23]. Additionally, the application of 5 t/ha of composed straw and 5 t/ha of mature decomposed Purun Tikus (Eleocharis dulcis) has been effective in reducing the concentration of Fe in acid sulfate tidal land [24]. This indicates the significance of organic amendments, such as humic acid and decomposed plant material, in addressing issues related to excess Fe in acid sulfate soils.

3.3 The impact of humate-Si on rice yield

The humate-Si soil ameliorant demonstrated the ability to enhance both the yield and yield components of rice, as depicted in Figs. 3 and 4. Across all formulas, there was a noticeable increase in panicle length and the number of panicles. Notably, soil ameliorant formulas F2, F3, and F4 exhibited the best performance in terms of panicle length, while treatments F2 and F0 demonstrated the highest number of panicles (as shown in Fig. 3). This suggests that the application of these soil ameliorants positively influenced key aspects of rice plant development and yield.

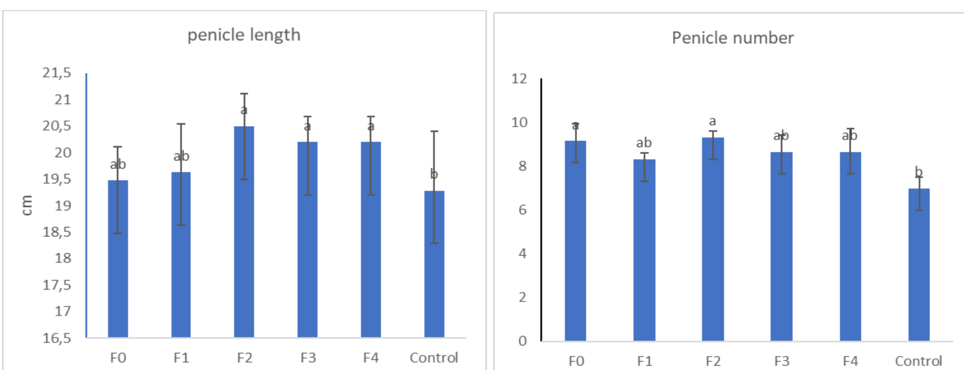

Fig. 3. The impact of humate-Si soil ameliorants on panicle length and number of rice panicles.

The humate-Si soil ameliorant demonstrated a notable impact on rice yield, with the F3 formula treatment showing the highest milled dry grain yield, as illustrated in Fig. 4. Silicon (Si) plays a crucial role in mitigating the uptake of iron (Fe) and aluminum (Al) under toxic conditions. Previous studies suggest that the application of Si in rice cultivation can lead to a substantial increase in grain yield, up to 50.8% [15]. This emphasizes the positive influence of Si in enhancing rice productivity and mitigating the effects of Fe and Al toxicity. Indeed, silica (Si) has the potential to decrease the solubility of heavy metals in swampy soils. Introducing Si elements into the soil has been observed to enhance the tolerance of rice plants to a range of stresses, both biotic and abiotic. This includes increasing resistance to various biotic stresses [25, 26], as well as providing a degree of resilience to abiotic stresses, such as exposure to toxic metals. The positive effects of Si in these contexts highlight its role in promoting plant health and adaptation to challenging environmental conditions [27-30]. 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 [31, 32].

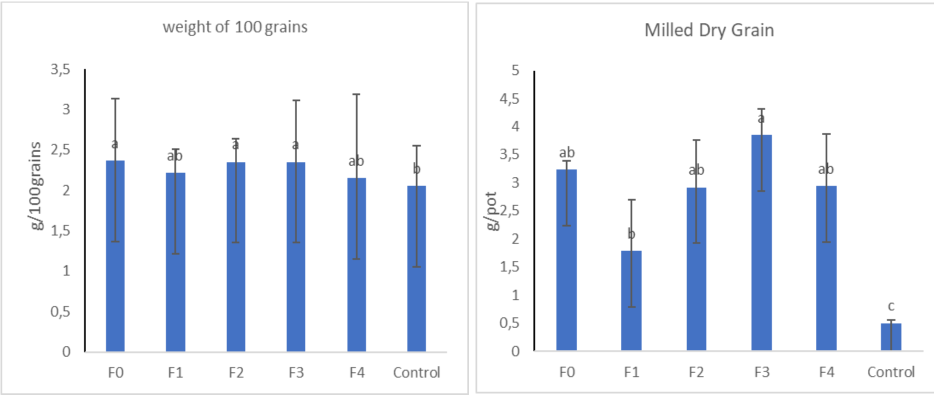

Fig. 4. The impact of humate-Si soil ameliorant on rice yield.

According to Bourbonniere and Creed [33], humic and fulvic acids play a role in contributing to the negative charge of the soil, functioning as organic colloids. Specifically, humic compounds have been shown to reduce Al-dd from 5.99 me/100 g to 5.33 me/100 g [34]. The application of humic materials in acid-sulfate soils is significant due to their ability to suppress iron (Fe) solubility. Humic materials are capable of chelating toxic elements in the soil, rendering them harmless to plants [35]. This underscores the importance of humic substances in addressing soil challenges and promoting plant health in acid-sulfate environments.

Iron (Fe) toxicity in rice, stemming from elevated levels of soluble Fe, represents a significant limitation in rice production [36]. Various soil amelioration strategies have been explored to address this issue. For example, combining lime with "Porre" organic fertilizer has been found to increase rice yields by more than 17% compared to using lime alone [20]. Additionally, the amelioration of acid sulfate land through a combination of agricultural lime, manure, and biochar resulted in the highest rice yield recorded, reaching 3.96 t/ha of milled dry grain [37]. These findings highlight the importance of integrated soil management practices in mitigating Fe toxicity and enhancing rice production.

4 Conclusion

The Si-humate soil ameliorant formula had a discernible impact on various soil and plant parameters, including soil iron (Fe) concentration, soil pH, Fe content in the roots and crowns of rice plants, and rice yields. The findings indicate that soil ameliorant formula F1 could increase pH, and decrease Fe^{2+} concentration, and showed no significant difference from formula F3. Formula F3 demonstrated effectiveness in reducing Fe toxicity and increasing rice yields. Notably, this formula was found to reduce the reliance on agricultural lime while concurrently enhancing rice productivity in tidal land.

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