Improving productivity of rice yield on tidal swampland using soil amendment

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Abstract. The main problems faced in the development of acid sulphate soils as agricultural land include: the presence of a pyrite layer, high soil acidity, high metal element solubility, and low nutrient availability. The objective of the paper was to describe the efforts to improve the productivity of acid sulfate soils through the provision of ameliorant. Amelioration is an effort to provide reactive materials into the soil with the aim of improving the physical, chemical and biological properties of the soil, so that soil productivity increases. The results showed that the application of ameliorant in the form of straw compost as much as 3.6 t ha$^{-1}$ in rice cultivation on acid sulphate land reduced the solubility of Al-dd soil up to week 8 and the provision of rock phosphate equivalent to 220 kg P ha$^{-1}$ could increase available P from 27.14 to 41.15 ppm P, Ca-dd from 0.14 to 0.24 cmol kg$^{-1}$, and acid sulphate soil pH from 3.42 to 3.63. Al poisoning damages the root system so that plants are susceptible to drought stress and experience nutrient deficiency which results in decreased of rice yields.

1. Introduction

The area of tidal swampland in Indonesia reaches 8.92 million ha, consisting of 7.55 million ha of tidal swampland on mineral soil and 1.37 million ha on peat soil. This land spreads across Sumatra covering an area of 3.02 million ha, Kalimantan (2.99 million ha) and Papua (2.43 million ha), while in Sulawesi about (0.32 million ha), Java (0.09 million ha) and Maluku (0.07 million ha). Tidal swampland, which has the potential to be used as paddy field, is around 2.80 million ha, consisting of 2.63 million ha of tidal swampland with mineral soil and 0.17 million ha of tidal swampland with peat soil. Tidal swamps with peat soils that have the potential to become rice fields are found in Riau, Bangka Belitung and Papua [1]. Based on these data, the opportunity to carry out agricultural extensification, especially for rice fields in tidal swamps, is still widely open.

Problems faced in the development of tidal swamps as paddy fields are soil acidity and low soil nutrient availability. Therefore, the provision of ameliorant is an effort for the success of rice cultivation in tidal swamps. Farmers in tidal swamplands generally do not provide ameliorant material in their paddy fields as recommended, even only a little is given. This shows that the farmers' knowledge about the use of ameliorant is insufficient so that the farming results obtained are low. The management of ameliorant materials and rice plants needs attention to get better rice yields [2].

The productivity of paddy fields in Indonesia according to [3] the national average is 5.2 t ha$^{-1}$ of GKG (GKG = Gabah Kering Giling in Bahasa or dry unhusked rice), the highest is in Bali (6.1 t ha$^{-1}$ of GKG), Sumatra (5.1 t ha$^{-1}$ of GKG), Sulawesi (4.6 t ha$^{-1}$ of GKG) and the lowest was in Kalimantan (3.4 t ha$^{-1}$ of GKG). The difference in productivity is caused by various factors, including: (1) type of paddy field, (2) type of soil, (3) management level and (4) rice varieties planted. Likewise, the types of paddy

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fields consists of irrigated, rainfed, tidal swamps and swamps. The potential yield of unhulled rice obtained in tidal swamps by applying appropriate management technology can reach 4.5 to 5.5 t ha\(^{-1}\) GKG.

Generally, the natural productivity of tidal swamplands is classified as low to moderate and to increase it, it is better to carry out land amelioration. Land amelioration is an effort to provide ameliorant to the soil with the aim of improving the physical, chemical and biological properties of the soil, so that the growth and production of rice plants can be increased. Ameliorants are reactive substances that can improve acidity and increase soil fertility by improving soil physical, chemical and biological conditions. Some examples of ameliorant materials commonly used to improve the productivity of tidal marshlands include: organic matter, rock phosphate and lime. The provision of organic material which is commonly carried out by farmers in tidal swamps is usually in the form of returning the leftover rice straw to the rice fields. The objective of the paper was to describe the efforts to improve the productivity of acid sulfate soils through the provision of ameliorant.

2. Soil nutrient status

Acid sulphate soils have specific properties according to land use and typology. The development of tidal swamps with acid sulfate soils for rice cultivation faced several obstacles, including: (1) soil acidity, (2) the high solubility of ferrous iron ions (Fe\(^{2+}\)), hydrogen (H\(^{+}\)) and hydrogen sulfide (H\(_2\)S) in reductive condition, (3) the high solubility of aluminum ions (Al\(^{3+}\)) under oxidative condition, and (4) the low availability of phosphorus (P) and potassium (K) nutrients.

The acidity of acid sulphate soils is influenced by several factors, including: the presence of pyrite, iron oxide-hydroxide minerals, sulfates, organic matter, neutralizing agents and hydrological conditions of the land. Each factor can interact with each other causing the dynamics of soil acidity. Soil acidity may not change or change in a significant way due to the large soil buffering capacity. The presence of pyrite minerals in the soil sulfidic material layer has a major role in determining the occurrence of the soil acidification process, especially due to the drop in the groundwater level. The hydrological conditions of the land have no significant effect on the dynamics of soil acidity, because the factors that influence redox changes are of low quantity or quality, for example low levels of Fe\(^{2+}\) and organic matter [4].

Aluminum poisoning usually occurs in oxidized soil conditions accompanied by P deficiency, because P is bound by Al to form Al-P which is not available to plants. Toxicity of (Fe\(^{2+}\)) and H\(_2\)S generally occurs in reductive soil conditions and contains lots of organic matter. Therefore, the solubility of Fe\(^{2+}\), Al\(^{3+}\), SO\(_4^{2-}\) ions in water reaches its peak at the beginning of the rainy season and gradually decreases until it enters the rainy season [5]. High soil acidity can affect the balance of chemical reactions in the soil and the availability of nutrients, especially phosphate. The low level of the natural fertility of acid sulphate soils in tidal swamps is closely related to the characteristics of the land.

The availability of nutrients in tidal marshlands, acid sulphate soils, is generally in low to very low conditions. Several research results indicate that the availability of N 0.22% to 0.49% (moderate) tends to decrease as the soil depth increases. The available P content is 12.6 ppm (very low) to 19.3 ppm (moderate), exchangeable K is usually moderate to high (0.37-0.89 cmol (+) kg\(^{-1}\)). Total P-content varies from low to very high levels, with an average of 45 mg 100 g\(^{-1}\) or being at high levels, the total-K content of 73 to 81 mg 100 g\(^{-1}\) very high level. The dominant exchangeable bases are Mg and Na. Availability of Mg at moderate to high levels (8.30-9.25 cmol (+) kg\(^{-1}\)) while Na at high levels (9.70 cmol (+) kg\(^{-1}\)). Conversely, the exchangeable Ca generally ranges from low to moderate (3.49-4.12 cmol (+) kg\(^{-1}\)). The soil cation exchange capacity usually varies from 33.5 to 37.2 cmol (+) kg\(^{-1}\) (high to very high), base saturation varies from 40% to 42% (low to moderate). Al saturation ranges from 67% to 71% (moderate to very high). The soil organic matter content in the soil surface varies between 7.51% to 10.93% or high to very high levels, the C/N ratio varies from high (25) to very high (39) [6, 7]. The results of soil analysis in each land typology and hydro-topography types in the tidal swamp are shown in table 1. Table 1 shows that the soils in acid sulphate tidal swamp land type B have a better fertility rate compared to the soils in type C.
Table 1. Soil chemical properties with a depth of 0 to 30 cm in various types of hydro-topography, tidal marshlands, South Kalimantan and Central Kalimantan.

| Soil chemical properties | Types of hydro-topography |
|--------------------------|---------------------------|
|                          | Type A | Type B | Type C |
| pH                       | 4.38   | 3.85   | 3.72   |
| C_organic (%)            | 6.81   | 7.69   | 7.40   |
| N_total (%)              | 0.45   | 0.52   | 0.40   |
| P_2O_5 tersedia (ppm)    | 7.98   | 8.25   | 2.50   |
| Exchangeable cations:    |        |        |        |
| K (cmol (+) kg^-1)       | 0.35   | 0.41   | 0.61   |
| Ca (cmol (+) kg^-1)      | 3.77   | 0.57   | 0.95   |
| Mg (cmol (+) kg^-1)      | 0.67   | 0.65   | 0.85   |
| Al (cmol (+) kg^-1)      | 5.20   | 6.44   | 14.25  |
| Fe (ppm)                 | 71.22  | 412    | -      |

Source: [2]

3. Problem in acid sulphate soil

The development of acid sulphate tidal swamplands as agricultural land faces several obstacles because this soil has extreme chemical characteristics and a fragile ecosystem. These obstacles include: aluminum, iron and hydrogen sulfide toxicity and phosphate deficiency. Acid sulphate tidal swamplands generally have a high solubility of aluminum (Al). This is due to the high level of soil acidity which can lead to increase Al solubility. The aluminum found in soil solutions can be found in different forms depending on the pH value of the soil. The pH value is 4.0 in the form of Al (H_2O)_6^{3+}, pH 4.5 to 5.0 in the form of Al (OH)_{2+}, pH 5.5 to 6.0 in the form of Al (OH)_{2+} and pH > 6.0 in the form of Al (OH)_3 [8]. The form of Al that is absorbed by plant roots and which can poison is different in each type of plant and in plant parts. The part of the plant that first interacts with the soil is the root and this part is sensitive to Al-toxic [9]. Factors that can cause Al poisoning include: 1) Al concentration in soil solution, 2) soil pH, 3) soil type, 4) plant age and 5) soil P availability.

Aluminum toxic can reduce and damage root systems, leaving plants vulnerable to drought stress and nutrient deficiency [10]. The initial symptom seen in rice plants is an inhibition of the root system as a result of disrupted root cell elongation [11]. Plants that experience Al stress, will damage the roots such as thickening, rolling and shortening. If plants experience Al stress for longer time, it can inhibit cell division [12]. According to [13] damage to the roots of rice plants is closely related to the accumulation of Al at the root tips, especially in the 0 to 5 mm area from the root tips. The area of damage to plant roots caused by Al was about 1 mm from the root tip [14]. Then [15] stated that high Al concentrations can damage the roots while they are still in the root cell walls, without having to enter the cells.

Acid sulphate soils that are in reductive conditions, have increased soil pH and decreased Al solubility. This condition can lead to increased solubility of Fe^{2+}, H_2S, CO_2 and organic acids which can toxicity plants [15]. The high concentration of Fe^{2+} ion in the soil can cause toxicity of plants, especially to rice plants. The level of rice toxic from 100 ppm with a pH of 3.7 to 300 ppm at a pH of 5.0 [16]. Meanwhile, the concentration of Fe^{2+} in rice plant tissue that can be toxic to plants is between 300 to 500 ppm [16] 500 to 2,000 ppm [17].

Iron toxic causes physiological changes in rice plants. The results of research in acid sulphate tidal swamplands (KP. Belandean) showed that rice genotypes gave different responses to Fe toxic, which was shown by different results, ranging from 2.24 to 5.09 t ha^{-1} and scoring of Fe toxic ranged from 1.3 to 6.3 t ha^{-1}. The Fe scoring value shows how heavy the toxicity of rice plant is, the higher scoring value the heavier the Fe toxic plants and conversely the lower scoring value the lighter the toxicity. The score
of 5 indicates that the plant is sensitive to Fe toxic, while the value of 3 indicates that the plant is tolerant to Fe toxic. Rice tolerant to Fe toxic showed higher grain yields than rice that was less tolerant or intolerant [18].

The high solubility of Al and Fe in soil solution can lead to binding of P by Al and Fe to form Al-P and Fe-P. As a result, the availability of P nutrients for plants becomes less available. P deficiency can be the main cause of stunted plant growth. Rice plants that are deficient in P show symptoms, among others: stunted, small tillers, tapered leaves, and dark green. H₂S poisoning generally occurs in acid sulphate tidal swamps which have poor drainage. The level of H₂S poisoning will be higher if the soil organic matter content is high. In the reduced condition, the solubility of H₂S has increased and can even poison rice plants. [15]. Plants that are poisoned by H₂S are very susceptible to infection by pests and plant diseases.

4. Amelioration in acid sulphate soil

Ameliorant materials commonly used to improve the productivity of tidal swamps with acid sulphates include: (1) straw, (2) rock phosphate, and (3) lime. Organic material that has the potential to be used as ameliorant in paddy fields is rice straw. The entry of the livestock sector into the farming system causes farmers to no longer return rice straw in the form of organic matter to rice fields, but to process it as animal feed. Decomposed organic material is a source of nutrients and will produce hydroxyl and carboxyl functional groups. These functional groups can bond Al, Fe, Mn and other microelements, thereby reducing the reactivity of these elements [19]. In acid sulphate soils that have a low pH, the Fe ion has a relatively stronger bonding ability. The results of [20] showed that giving straw compost as much as 3.6 t ha⁻¹ to rice cultivation on acid sulphate land reduced the Al-dd soil solubility up to week 8.

Rice straw also contains microelements such as Zn, Si and Fe [21]. The positive impact of decomposition of organic matter is an increase in the availability of soil nutrients for plants. Application of crop residue (straw) that is immersed at the beginning of the growing season can increase the availability of N for plants [22]. Under reductive conditions and an excess amount of organic matter can hurt plant growth due to the solubility of organic acids and metal elements [21]. Meanwhile, [23] reported that giving rice straw can reduce the pH of the paddy soil because in anaerobic conditions microorganisms can produce organic compounds that are toxic to plants. The application of organic matter not only affects the chemical properties of the soil but also affects the physical and biological properties of the soil. The presence of organic acids can lower soil pH, form acetic acid complexes, and release organic acids into the soil solution. In addition to the mineralization process, the increase in nutrient availability can be through the indirect influence of organic matter such as the binding of metal elements and the reduction process of Fe³⁺-P to Fe²⁺-P. Organic acids in the soil can reduce P fixation by Fe and Al through the chelation mechanism [24].

Organic matter can cause an increase or a decrease in nutrient loss through leaching. Dissolved P losses increase when organic matter is added to the soil. Organic matter can be a source of P which is lost significantly from the land through the runoff, although the effect is still lower when compared to the addition of inorganic fertilizers and manure together. Phosphate lost from the soil can come from the soil, residual plant material, inorganic fertilizers, manure or artificial green manure [25]. Many research results indicate that the return of organic matter to the land reduces the use of inorganic fertilizers. The return of organic matter to the land can cause a decrease in soil quality or further decrease the yield of rice obtained. This can occur due to the low quality of the organic material given. The quality of organic matter depends on the rate of decomposition and the amount of nutrient released to the soil [26]. According to [27] that relatively raw organic matter can reduce soil pH, then [28] stated that compost with a finer texture has a greater effect on the soil than compost with a coarse texture.

The application of organic matter can cause a decrease in the number of rice tillers. This is due to an increase in the concentration of Fe²⁺ and a decrease in soil pH so that it affects the growth of rice plants [29]. The application of organic matter can cause an increase in the concentration of Fe²⁺ in the soil and decrease the soil pH [30]. Rice straw that is given to the land before rice planting begins must be in a
relatively decomposed condition because in that condition, rice straw can become a source of nutrients and has a smaller reducing effect. The results of the research by [31] show that giving crop residue (straw) and a mixture of straw and manure can increase rice yields (figure 1). The increase in rice yields continued to occur due to the improvement in the environmental conditions for growing plants due to continuous organic ameliorants, such as improved soil structure and increased soil organic content.

![Figure 1](image.png)

**Figure 1.** Production of margasari rice variety in dry season from 2003 to 2005 in acid sulphate soils with several treatments of rice straw measures [31].

Rice straw application must be effective because in excess amount it will not have a real impact in increasing production. The results of the 2003 to 2007 Balittra research show that giving 5 t ha$^{-1}$ of straw can produce results that are not different compared to higher doses. This indicates that the return of the remaining crop straw residue of about 5 t ha$^{-1}$ from the previous crop was sufficient to improve the growing conditions of rice plants.

Another ameliorant used to improve soil fertility is rock phosphate. Land amelioration with rock phosphate aims to overcome the problem of P deficiency and acidity in acid sulphate soils in tidal swamps. Rock phosphate fertilizers are minerals which mostly contain calcium phosphate or apatite ($\text{Ca}_{10}(\text{PO}_4)_6\text{F}_2$) in the form of powder which can be applied directly. Apart from containing by-products such as Ca and Mg, this fertilizer is also slow release so it is suitable for acid soils with a residual effect that is long enough for up to 3 years. The effect of rock phosphate depends on the quality, P content, and the nature of the reaction it causes.

Treatment of types and doses of rock phosphates did not show a different effect on rice yields, although in general it was seen that rock phosphates from Algeria showed higher yields than the other two types of rock phosphates at a rate of 250 kg ha$^{-1}$ (figure 2). The application of rock phosphate was able to increase the availability of P through a dissolving reaction that occurred under acidic conditions. Soil acidity is a major factor in dissolving rock phosphate in acid sulfate soils. Based on the rice yields obtained in 2005, the Moroccan rock phosphate gave more stable yields. This yield stability is related to the high solubility of P and the residual P effect of Moroccan rock phosphate. Under the character of
each rock phosphate, its ability to provide P depends on the dissolving process of rock phosphate based on the form of the bond between P and Ca in the rock phosphate.

Application of rock phosphate can increase soil pH due to the release of $\text{Ca}^{2+}$ and $\text{H}_2\text{PO}_4^-$ ions into the soil. Rock phosphate is an excellent ameliorant material applied directly to acid sulfate soils, because of its acidic soil conditions and high $\text{H}^+$ solubility. $\text{Ca}^{2+}$ and $\text{H}_2\text{PO}_4^-$ ions can suppress the solubility of $\text{Al}^{3+}$, $\text{Fe}^{2+}$, and $\text{H}^+$ ions in soil solution, so that soil pH increases. Giving natural philosophy equivalent to 220 kg P ha$^{-1}$ can increase P-available from 27.14 to 41.15 ppm P, Ca-dd from 0.14 to 0.24 cmol (+) kg$^{-1}$, and acid sulphate soil pH from 3.42 to 3.63 [32].

![Figure 2](image_url)

**Figure 2.** Grain yields were obtained as a result of rock phosphate residue treatment (giving in 2004) [31].

Application of lime can reduce soil acidity. Some research results indicate that lime application can reduce the solubility of $\text{Al}$, $\text{Fe}$, $\text{Mn}$ and $\text{SO}_4$ elements in soil solutions, and increase soil pH. The rate of reduction in the solubility of these elements is determined by various factors, including: the initial content of these elements, soil buffering capacity, initial soil pH, the amount and source of lime given, lime application techniques, and others [33]. Between acid mineral soils in swamps and dry land is the content of organic matter. The surface of the tidal marshlands of acid sulphate soils was previously covered by a layer of organic matter (peat). Therefore, the levels of organic matter in acid sulphate soils are high to very high, as seen from several analyses of acid sulfate soils proposed by [33] and [34]. High soil organic matter content causes high soil buffering capacity, so applying lime to increas soil pH requires a very large amount.

Applying lime to acid sulphate soils is primarily not to increase soil pH, but to improve the chemical environment of plant roots and meet the nutrient needs of Ca and Mg. Rice and secondary crops can grow normally in a pH range of 4.3 to 4.5 in acid sulphate soils, no need for an optimal pH range of of 5.5 to 6.5. The main key lies in the use of acid-tolerant varieties and good water management. Summarizing some results of Balitra's research during the 1984 to 2012 period, it was concluded that potential acid sulphate soils with a pH <4 need to be given dolomite lime of 2 to 3 t ha$^{-1}$, but if pH >4 is sufficient to give 1 t ha$^{-1}$ [33], while [35] show that 3 to 4 t ha$^{-1}$ of lime is sufficient for actual acid sulphate soils.

Determination of the need for lime for acid sulphate soils can be done through the incubation method titration and Al-dd. The incubation method is carried out by mixing lime, soil, and water in several measures of lime for one week to several weeks, then the need for lime is determined according to the
desired pH value. The weakness of this method is the accumulation of salts (Ca, Mg, and K) so that the lime dose can be more than it should be [36]. Then the 0.05 N NaOH titration method was carried out to reach a certain pH, this method required a lower amount of lime when compared to the incubation method and Al-dd KCl 1 N. The results of research in greenhouses and in the fields showed that the determination of the amount of lime was based on titration and incubation can be applied in tidal swamplands [37].

Dolomite application 2 t ha$^{-1}$ and SP-36 200 to 300 kg ha$^{-1}$ obtained an average rice yield of 4 t ha$^{-1}$ on potential acid sulphate soils in Telang District, Muba Regency, South Sumatera [38]. On potential acid sulphate soils in Tabunganen, South Kalimantan, the yield of rice by giving 43 kg P ha$^{-1}$, 52 kg K ha$^{-1}$, lime 1 t ha$^{-1}$ and manure 5 t ha$^{-1}$ reached 3.24 t ha$^{-1}$. Meanwhile [36] stated that in Belawang, South Kalimantan, the need for lime was higher, namely 4 t ha$^{-1}$. This situation is caused by the presence of pyrite in the actual acid sulphate soil which has undergone oxidation so that the Al-dd is high.

5. Conclusions

Improvement of soil fertility can increase the growth and yield of rice plants. Application of lime can increase soil fertility by decreasing soil acidity, reducing the solubility of Al, Fe, Mn and SO4 elements in soil solution, and increasing soil pH. Rice straw is the main ameliorant material produced in tidal swampy fields and land amelioration with ripe rice straw (compost) can improve soil fertility through increasing nutrient availability, chelating toxic elements to plants and increasing rice production.

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The authors state that the positions of all authors are equal as main contributors.

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