Characterization of steel slag and its effect on rice production in Latosol and acid sulfate soil

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Abstract. Most soils in Indonesia need soil ameliorant material. There are various ameliorant materials that can improve soil properties. The researchers propose steel slag as an alternative ameliorant material. Steel slag is a waste from steel manufacturing, and the amount is very abundant. Unfortunately, steel slag falls into the category of hazardous and toxic waste (by regulation). It is still questionable and needs verification that this material is potential for agriculture. In this study, an analysis of the characteristics (total chemical and micronutrient content) of steel slag was carried out. Besides, the steel slag was applied to Latosol and Acid Sulfate Soil (ASS) planted with rice plant to see its effects on it. The results show that steel slag is rich in Ca, Mg, P, Si, micronutrients, and low in heavy metals. The steel slag application for rice plants on Latosol and ASS show a positive effect. Rice production on soil with steel slag addition is higher than control. The optimum doses of steel slag are 6 tons/ha for Latosol and 9 tons/ha for ASS. It indicates that steel slag is a potential ameliorant material and needs reconsideration to exclude it from its category as hazardous and toxic waste.

1. Introduction

Indonesia has many types of soils which its characteristics are influenced by soil-forming factors. The characteristics of the parent material of the soils, which are mostly acidic to intermediate and coupled with the influence of the humid tropical climate, cause the soils found to be generally acidic with low content of macro- and micronutrients. These soil properties affect the growth and production of the plant on it. Such soil properties require soil amendment/ameliorant materials so that soil properties become better and are more suitable for growing plants. The soil ameliorant material is a substance that is added to the soil to improve soil quality and increase the growth and production of plants.

There are various types of soil ameliorant materials which can improve soil characteristics. One of the soil ameliorant materials that is potential to enhance the quality of soil is steel slag. Steel slag is a by-product formed from the production process of steel manufacturing. Until now, steel slag is still included as hazardous and toxic waste that can endanger the health or survival of humans, other creatures, and, or the environment in general. Some analysis results of steel slag stated that it does not contain heavy metals exceeding the permissible threshold and even many macro and micronutrients that can be used for plants. Steel slag can be divided into iron-making slag (blast furnace slag) and steelmaking slag (converter slag and electric furnace slag). Steel slag is a waste that is very abundant in Indonesia and Japan.
Many countries, like the United States, Japan, and Germany have utilized steel slag as a soil ameliorant for years. Meanwhile, in Indonesia, steel slag usage is categorized as still rare [1], but steel slag is very potential as soil ameliorant material. The application of steel slag generally expects that the Si element in the steel slag can be utilized by plants. However, in the steel smelting process, a lot of lime is added to the furnace so that the steel slag function as lime. Therefore, the function of steel slag may be more critical as a lime material compared to a Si source.

Based on previous research, steel slag can be an alternative soil ameliorant because it can increase macro- and micronutrients even in peat soils [2]. [3] stated that the application of steel slag as an ameliorant on peat soil gives a significant effect such as increasing pH, base saturation, exchangeable-Ca and -Mg content, and also increasing nutrient content (Ca, Si, ash content, and Fe). [4] mentioned that Indonesian steel slag (electric furnace slag) can be used in agriculture as (a) liming material, (b) Si fertilizer in lowland rice plants, and (c) peat soil enhancer. As a liming material, the effect of electric furnace slag on plant growth tends to be better than that of calcite or dolomite. [5] mentioned in their research journal that regardless of the type of slag, these by-products have agronomic viability and can be applied in a no-tillage system with efficiency similar to that of lime for the neutralization of soil acidity in the surface and subsurface layer. In the no-tillage implementation, surface application of slag ameliorates soil acidity and allows for adequate nutrition and yield of the soybean crop.

The utilization of steel slag in Indonesia is limited because there is a Government Law No. 101 year 2014 (about The Management of Hazardous and Toxic Waste) that categorized steel slag as hazardous and toxic waste. It is still questionable and should be proven that this material is potential for agriculture. Hence, the objectives of this study were 1) to identify the characteristics of steel slag, especially to evaluate the content of heavy metals in steel slag (from Sumitomo Metal Industry (SMI) Japan and Krakatau Steel (KS) Indonesia) and 2) to analyze the effect of steel slag on rice production, tested on Latosol and Acid Sulfate Soil (ASS).

2. Materials and methods

The experiment was conducted in the greenhouse of University Farm and the laboratory of the Soil Science and Land Resources Department, IPB University. Materials used in this research were steel slag, sample of Latosol, sample of Acid Sulfate Soil, rice seed, fertilizers, and other materials for greenhouse and laboratory analysis. The Acid Sulfate Soil samples were obtained from Rantau Rasau District, East Tanjung Jabung Regency, Jambi Province. Meanwhile, the Latosol samples were obtained from University Farm, IPB University, Dramaga Campus, Bogor, West Java Province. Soil samples were taken at a depth of 0-20 cm. Rice variety Inpari 1 was used as an indicator plant. Three types of steel slag were used in this study, named blast furnace slag (BF) and converter slag (C) from Sumitomo Metal Industry (SMI) Japan and electric furnace slag (EF) from Krakatau Steel (KS) Indonesia.

To identify the characteristics of steel slag, we carried out the total chemical analysis (for converter slag, blast furnace slag, and electric furnace slag) and micronutrient content with DTPA (Diethylene Triamine Penta Acetic Acid) extraction (for converter slag and blast furnace slag). After that, to see the effect of steel slag on rice production, steel slag was applied to two different types of soil, namely Latosol and Acid Sulfate Soil (ASS). Steel slag used in this experiment was converter slag (C) from Sumitomo Metal Industry (SMI) Japan. On each soil, rice plant was planted. This steel slag application was conducted in a greenhouse with a completely randomized design. There were four levels of treatment for each soil. The doses of steel slag used were 0, 3, 6, and 9 tons/ha. The codes for steel slag application on Latosols were L0 (0 ton/ha), L1 (3 tons/ha), L2 (6 tons/ha), and L3 (9 tons/ha). Meanwhile, the codes for steel slag addition on Acid Sulfate Soil (ASS) were S0 (0 ton/ha), S1 (3 tons/ha), S2 (6 tons/ha), and S3 (9 tons/ha). Soil samples were put into pots and then added with converter slag (C) according to the treatment. Then, the soil is loosened and incubated for 14 days. Rice seeds were sown and transferred to pots at the age of 14 days (2 weeks). Fertilizers of Urea, SP-18, and KCl also were used for each treatment at the standard rate. Each treatment was replicated three times. The experimental parameters of both soils were rice production quantity and production increment.
3. Results and discussion

3.1. Characteristics of steel slag

The result of the characteristic analysis of steel slag is presented in Table 1 (total chemical of three types of steel slag).

**Table 1. The total chemical of three types of steel slag (converter slag, blast furnace slag, and electric furnace slag)**

| Composition | Converter Slag (SMI)** | Blast Furnace Slag (SMI)** | Electric Furnace Slag (KS)*** |
|-------------|------------------------|----------------------------|------------------------------|
| SiO₂        | 6.57                   | 32.22                      | 14.08                        |
| TiO₂        | 0.57                   | 0.87                       | 0.42                         |
| Al₂O₃       | 2.05                   | 14.50                      | 13.71                        |
| Fe₂O₃       | 8.12                   | 1.06                       | 18.65                        |
| MnO         | 3.30                   | 0.38                       | 1.26                         |
| CaO         | 53.36                  | 41.17                      | 23.19                        |
| MgO         | 2.86                   | 5.52                       | 16.40                        |
| Na₂O        | 0.19                   | 0.41                       | 0.34                         |
| K₂O         | 0.01                   | 0.33                       | 0.10                         |
| P₂O₅        | 0.84                   | 0.04                       | 0.16                         |
| S           | 0.13                   | 0.86                       | 0.11                         |
| ZnO         | -                      | -                          | 0.131                        |
| PbO         | -                      | -                          | 0.011                        |
| ZrO₂        | 0.007                  | 0.551                      | 0.027                        |
| HfO₂        | -                      | 0.008                      | -                            |
| Cs₂O        | 0.013                  | -                          | -                            |
| CuO         | 0.002                  | -                          | 0.016                        |
| SrO         | 0.040                  | 0.071                      | 0.045                        |
| V₂O₅        | 0.106                  | 0.006                      | 0.162                        |
| Cr₂O₃       | 0.025                  | -                          | 0.147                        |
| Co₃O₄       | 0.005                  | -                          | 0.011                        |
| Cl           | 0.017                  | 0.025                      | 0.021                        |
| BaO         | -                      | -                          | 0.025                        |
| Nb₂O₅       | 0.015                  | 0.006                      | 0.007                        |
| Sc₂O₃       | 0.008                  | -                          | -                            |
| Rh₂O₃       | 0.003                  | -                          | -                            |
| Y₂O₃        | -                      | 0.013                      | -                            |
| CeO₂        | -                      | 0.011                      | -                            |
| LOI*        | 18.96                  | 1.96                       | 11.25                        |

Notes: *LOI: Loss of Ignition, ** SMI: Sumitomo Metal Industry Japan, *** KS: Krakatau Steel Indonesia
Of the three types of steel slag analyzed, several elements had a large amount. Some of these elements are Silicon/Si (in the form of SiO₂ is about 6-32%), Aluminium/Al (in the form of Al₂O₃ is about 2-14%), Iron/Fe (in the form of Fe₂O₃ ranging from 1.06-18.65), Calcium/Ca (in the form of CaO measured 23-53%), and Magnesium/Mg (in the form of MgO is about 2-16%). Apart from the elements above, in the steel slag, many other elements can be useful for plant growth, and the elements which are categorized as heavy metals (although the percentage in steel slag (converter slag, blast furnace slag, and electric furnace slag) were very low).

The presence of Si, Ca, and Mg, which were high enough in the steel slag, has the potential to be used as a soil ameliorant material. In general, the percentage of Ca in steel slag is higher than Si. The elements of Ca and Mg are classified as macronutrients, which are very beneficial for plant metabolism, so that affect the plant growth and its yield. Besides, the high presence of Ca and Mg have a liming effect on the soil. Even [4] stated that the addition of steel slag could increase soil pH more effectively than calcite or dolomite. The high Ca and Mg percentage in steel slag and the effect of increasing soil pH mean that the steel slag can be called as an excellent lime material. Element Si is a nutrient that is very useful for plants such as rice plant, bamboo, sugarcane, and the other plants from the Gramineae family. In the steel slag, the content of Si reached 32.22% (from blast furnace slag), 14.08% (from electric furnace slag), and 6.57% (from converter slag). It indicates that steel slag can be utilized as a source of Si fertilizer for plants. Besides, according to [6], steel slag is one of the low-cost sources to supply Si for rice plants. From the total chemical above, we know that the largest percentage of Si, Ca, and Mg respectively were in blast furnace slag, converter slag, and electric furnace slag.

On the other hand, we also can see in Table 1 that the amount of Fe in steel slag from Krakatau Steel (KS) Indonesia (in the form of Fe₂O₃ was 18.65%) is higher than from Sumitomo Metal Industry (SMI) Japan (in the form of Fe₂O₃ were 1.06% and 8.12%). It shows that the extraction process of iron (Fe) in KS is less optimal than SMI. In this total chemical table, there are many heavy metals in steel slag. Nevertheless, the percentage of heavy metals are commonly very low (less than 0.5%). It indicates that steel slag is safe for the environment and plants when it is applied to the soil. Therefore, it needs reconsideration that steel slag should be excluded from the hazardous waste list (on Government Law No. 101 year 2014 about The Management of Hazardous and Toxic Waste). So, the utilization of steel slag for agriculture can be more optimal in Indonesia.

Table 2 presents the result of the micronutrient content of steel slag (converter slag and blast furnace slag). Four micronutrients analyzed were Copper (Cu), Zinc (Zn), Iron (Fe), and Manganese (Mn).

Table 2. The micronutrient content of steel slag (DTPA extraction)

| Micronutrient Element | Converter Slag | Unit | Blast Furnace Slag* | Unit |
|-----------------------|----------------|------|---------------------|------|
| Cu                    | 0.46           | ppm  | 3.04                | ppm  |
| Zn                    | 1.20           | ppm  | tr                  | ppm  |
| Fe                    | 3.42           | ppm  | 0.12                | %    |
| Mn                    | 230.95         | ppm  | 12.79               | ppm  |

*tr: unmeasurable

Micronutrient elements are essential for plant growth. The solubility of micronutrients in this study was extracted with DTPA (Diethylene Triamine Penta Acetic Acid) solution. The dissolved Cu element was 3.04 ppm in the blast furnace slag and 0.46 ppm in the converter slag. Zinc element in the converter slag is measured at 1.20 ppm, while in the blast furnace slag is not measured (tr). The dissolved Fe element from the blast furnace slag (0.12%) was higher than the converter slag (3.42 ppm). The dissolved Manganese (Mn) from the converter slag was 230.95 ppm and higher than the blast furnace slag.

The presence of microelements in the steel slag can be a source of micronutrient elements for the plants. Although the amount needed by the plant is relatively low, the presence of micronutrient elements are significant for plant metabolism. Table 2 shows that the elements Fe and Mn are elements that have relatively high solubility. The role of iron for plants is as a part of the protein that functions as
an electron carrier in the light phases of photosynthesis and respiration. According to [7], iron (Fe) plays a role in the formation of chlorophyll. Therefore, the optimal availability of Fe is needed by plants. If the iron in the nutrient solution is insufficient, the formation of chlorophyll will not be perfect, not optimal respiration and the energy produced was small; consequently, the absorption of nutrients by root is slow.

The role of Manganese is as an enzyme activator (phosphate transfer enzyme and enzyme in Krebs cycle), oxidation-reduction reaction, metabolism of Nitrogen (N), chlorophyll and carbohydrates, an essential part of chloroplast and participates in a reaction that produces oxygen. The presence of Mn causes the photosynthesis process to run more smoothly. The increase in photosynthetic activity also affects the increase in chlorophyll concentration. The chlorophyll concentration will be denser so that the green condition of the leaves will also increase. This situation is because Mn plays an essential role in the formation of chlorophyll, even though the leaves are old. Manganese plays a critical function in photosynthesis, respiration, and nitrogen metabolism because Manganese forms a bridge between enzymes and their substrates [8]. Therefore, the presence of these micronutrients on steel slag can increase the growth and production of rice plants.

3.2. The effect of steel slag on rice production
The production of rice plants as the effect of steel slag (converter slag) addition is presented in Table 3 (for Latosol) and Table 4 (for Acid Sulfate Soil).

Table 3. The effect of steel slag on rice production tested on Latosol

| Treatments* | Weight of Total Grain (g/pot) | Weight of Filled Grain (g/pot) | Percentage of Filled Grain Weight (%) | Production Increment (%) |
|-------------|-------------------------------|-------------------------------|---------------------------------------|--------------------------|
| L0          | 42.03                         | 39.20                         | 93.27                                 | -                        |
| L1          | 43.84                         | 39.74                         | 90.65                                 | 4.32                     |
| L2          | 49.93                         | 48.56                         | 97.24                                 | 18.90                    |
| L3          | 45.92                         | 42.47                         | 92.48                                 | 9.67                     |

T0 (Latosol), L0 (steel slag dose 0 ton/ha), L1 (steel slag dose 3 tons/ha), L2 (steel slag dose 6 tons/ha), L3 (steel slag dose 9 tons/ha)

Table 4. Rice production on Acid Sulfate Soil

| Treatments* | Number of Filled Grains (per pot) | Number of Empty Grains (per pot) | Percentage of Filled Grains (%) | Weight of Filled-Unhulled Grains (g/pot) | Production Increment (%) |
|-------------|-----------------------------------|----------------------------------|---------------------------------|------------------------------------------|--------------------------|
| S0          | 727                               | 393                              | 64.91                           | 18.52                                    | -                        |
| S1          | 1378                              | 188                              | 87.99                           | 31.60                                    | 70.62                    |
| S2          | 1479                              | 291                              | 83.55                           | 35.32                                    | 90.71                    |
| S3          | 1890                              | 225                              | 89.36                           | 45.40                                    | 145.14                   |

S0 (Acid Sulfate Soil), S0 (steel slag dose 0 ton/ha), S1 (steel slag dose 3 tons/ha), S2 (steel slag dose 6 tons/ha), S3 (steel slag dose 9 tons/ha)

Table 3 and Table 4 show the effect of steel slag addition in Latosol and Acid Sulfate Soil on rice production (weight of filled grain (g/pot) and production increment (%)). The addition of steel slag have a positive effect on rice production in Latosol (Table 3). In general, the higher the steel slag dose given,
the higher production obtained. There was a production increment of L1, L2, L3 compared to L0 (control). The weight of filled grain of L0 (39.20 g/pot) was not much different from the result obtained when we added 3 tons/ha (39.74 g/pot) of steel slag (L1), and the production or yield only increased by 4.32%. Steel slag addition with a dose of 6 tons/ha (L2) produced filled grain of 42.47 g/pot. This dose gave 18.90% of production increment, which is the highest one. After the dose is increased to 9 tons/ha (L3), the increase in production is not higher than the dose of 6 tons/ha (L2). Based on this result, if we want to apply the steel slag on Latosol for rice plants, we should choose the steel slag (converter slag) dose at 6 tons/ha because it is the optimal one and gives the highest production increment.

Steel slag gave an effect in increasing the amount of filled grain, weight of filled grain, and percentage of total filled grain in Acid Sulfate Soil (ASS). The higher dose of steel slag given, the higher the percentage of the amount and weight of filled grain obtained. The highest weight of filled grain was S3 at 45.40 g/pot, and the lowest was S0 (control) at 18.52 g/pot. Table 4 also shows that adding steel slag to Acid Sulfate Soil (ASS) can increase the weight production of filled grain by 145.14% (S3) compared with S0 (control). An increase in growth and production of rice is an indirect effect of applying steel slag, which improves soil chemical properties. The results of this study support a research conducted by [9] that the addition of steel slag for rice plants can increase the percentage of filled grain and decrease the rate of empty grain.

Based on this research, we can see that the application of steel slag on different soil types will show different effects on the soil itself. Latosol and Acid Sulfate Soil (ASS) have different properties, especially in terms of soil acidity. Latosol has a higher soil pH than Acid Sulfate Soil. The difference in the effect of the addition of steel slag on rice production from each soil can be shown by the increase in production compared to each control. The highest production increment on Latosol and Acid Sulfate Soil respectively were 18.90% and 145.14% (compared with each control). The effect of steel slag on rice production can be seen to be very significant on Acid Sulfate Soil (ASS) because it has a very acidic pH (generally around pH 3). The addition of steel slag can increase soil pH. This increase in pH results from the presence of Calcium and Magnesium in the steel slag, which gives a liming effect. The increase in soil pH indirectly raised the growth and rice production (yield) in this research (compared with control).

4. Conclusion

Based on the results and discussions above, the conclusions of this study are:

- Steel slag is rich in Ca, Mg, Si, micronutrient elements and commonly low in heavy metals concentration.
- The steel slag application for rice plants on Latosol and Acid Sulfate Soil show a positive effect. Rice production on soil that was given with steel slag is higher than control. The impact of applying steel slag is different for each soil. The optimum doses of steel slag are 6 tons/ha for Latosol and 9 tons/ha for Acid Sulfate Soil.
- Steel slag is a potential soil ameliorant material for agriculture and safe for the environment when applied to the soil. Moreover, it needs reconsideration to exclude the steel slag from the hazardous and toxic waste list.

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