Reducing Production of CO_2 and CH_4 from Peaty Paddy Soils through Applying Slag in South Sumatera, Indonesia

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ABSTRACT

The change of anthropogenic peatlands to agricultural lands could have negative impacts, namely soil subsidence due to oxidation processes, and reduce the stock of soil organic carbon due to the increase of greenhouse gases (CO_2 and CH_4) emissions which contribute to global warming. Stability of converted peatlands could be increased through amelioration of soil by applying steel slag. A laboratory experiment was conducted with using factorial complete randomized design with ten combination treatments, including slag application, of peat soil samples collected from paddy fields in South Sumatera. This study determined the effect of steel slag application on reducing greenhouse gas (CO_2 and CH_4) production from cultivated peatland soils. The first factor of experimental treatment was peaty soil from 5 different locations, and the second factor was the application of steel slag. The highest production potentials of CH_4 and CO_2 were shown by peaty paddy soils from Kayu Agung and Plaju, respectively, while the lowest fluxes were shown by Indralaya's peaty paddy soil. Peaty paddy soil from the Indrajaya site produced the lowest CO_2 and CH_4 compared with other sites. Application of steel slag ameliorant reduced CH_4 and CO_2 emissions by 19.24% and 18.95%, respectively, on average. Slag ameliorant also reduced acidity of peaty paddy soils.

1. INTRODUCTION

The area of peat land in Indonesia is 14.9 million hectares (ha), most of which are distributed in Sumatera, Kalimantan and Papua (Wahyunto et al., 2014). Of the total area of peat, around 50.1% of the land is covered by forests, 10.5% by oil palm, 5.7% by other cereal crops and 2.3% by rice fields. About 44.6% of Indonesia peatland had been degraded (Masganti et al., 2014). Peat soils are degraded when the organic C content decreases from 38.91-57.24 g/kg to 30.62-41.83 g/kg and are a source of greenhouse gases (GHGs) emissions (Masganti et al., 2014). Peat also plays an important role as a long-term sink of GHG (Roulet et al., 2007). Improper management of peat is a source of greenhouse gas (GHG) emissions that contributes to global warming and climate change (Miettinen and Liew, 2010; Leng et al., 2019).

Tropical peatlands are a source of carbon deposits (70 Gt C) and nitrogen. Carbon stocks (C) in tropical peatlands vary with a range of 30-70 kg C/m^3 or 300-700 mg C/ha per meter of peat depth, while the C content in mineral soils at depths of 0-20 or 25 cm does not exceed 250 mg C/ha (Agus and Subiksa, 2008). Peatlands in Sumatera and Kalimantan are estimated to have a C stock varying in the range 2,000-3,000 Mg C/ha, which are potential sources of high C emissions. Organic matter in peat soil is naturally decomposed slowly and continuously. Drained peat accelerates decomposition rates, soil subsidence and carbon loss (Crozier et al., 2000; Hooijer et al., 2012). Carbon loss from peats used for agricultural cultivation ranges from <40 mg to <60 mg CO_2/ha/year on 70 cm of groundwater (Hooijer et al., 2012). The high water retention in peatland limits or impedes decomposition rate of soil organic matter, and lowering of peat water table increases organic matter mineralization and this subsequently enhances carbon losses (Leng et al., 2019)

The management of land use change of peatlands for agricultural activities greatly influences the rate of decomposition. Draining of organic soils for agricultural purposes increases the emissions of greenhouse gases (CO_2, CH_4, and N_2O) compared to

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undrained peat (Kasimir et al., 2018). Without appropriate management, peats are easily degraded and become a source of GHG emissions. In the reductive conditions of soil, the decomposition rate of organic matter is slow and produces a lot of poisonous organic acids and high methane (Rezanezhad et al., 2016), whereas in oxidative conditions the decomposition rate is rapid and much CO_2 is released (Nakonieczna and Stepniewska, 2014; Evans et al., 2019). The rate of decomposition under anaerobic or aerobic conditions affects the balance of CO_2 versus CH_4 production in peat rice soils (Rumbang, 2015). The rate of decomposition of peat determines the level of peat maturity or changes in the level of fibers content in peat soil (Sulistyono, 2000).

The peat utilization for lowland rice cultivation influences the dynamics of GHG emissions mainly carbon dioxide (CO_2) and methane (CH_4). CO_2 and CH_4 emissions contribute to the global greenhouse effect by 55% and 15%, respectively (Mosier et al., 1994; Olivier et al., 2017). The effect of CH_4 in the atmosphere on global warming is 21 times greater than CO_2 (IAARD, 2011). The methane concentration of 1.3 ppm in the atmosphere causes an increase in global temperature by 1.3°C. Anthropogenic global methane emissions in 2010 were 6,875 million mg of CO_2-e which is predicted to increase by 15% to 7,904 million mg of CO_2-e in 2020 (Global Methane Initiative, 2017).

Indonesia has committed to reduce GHG emissions from the sectors of peat, energy, waste, forestry, industry and agriculture by 26% independently or 41% with international cooperation. Based on Presidential Regulation No. 61/2011, the target for reducing GHG emissions from sustainable peat management is 103.98 million mg of CO_2-e (Ministry of Environment and Forestry, 2017).

Increased productivity of peat can be improved through amelioration, among others, by utilizing industrial waste such as slag. The iron and steel industry produces 20% of slag waste per ton of steel production which has the potential to negatively impact the environment and public health (Perdana and Sukandar, 2016). Slag waste management is based on the concept of reduce, reuse, recycle and recovery approaches. During this time, slag waste has been used as a mixture of cement construction materials and asphalt mixtures for road construction (Yahya, 2013; Perdana and Sukandar, 2016). Slag is an iron or steel smelting industrial waste in the form of small chunks obtained from the side results of steel making in a high temperature furnace. Steel slag has been reported to contain 40-43% CaO, 31-36% SiO_2, 13-15% Al_2O_3, and 4-6% MgO (Munir and Handayani, 2012). Slag is rich in lime (CaO), silicic acid (SiO_2), phosphoric acid (P_2O_5), magnesia (MgO), Mn, and Fe. These properties of the slag can be exploited to make use as a fertilizer (Das et al., 2019). Fertilizers made of slag are categorized as slag silicate fertilizer, lime fertilizer, slag phosphate fertilizer, and iron matter of special fertilizer (Das et al., 2019). The objective of this paper was to determine the effect of steel slag ameliorant on the production rates of CO_2 and CH_4 from peaty paddy soils.

2. METHODOLOGY

2.1 Soil sampling and experimental design

The research activities were carried out at the greenhouse gas laboratory, Indonesian Agricultural Environment Research Institute in Pati Regency, Central Java Province in October-December 2017. The peaty paddy soils were taken at the center of wetland rice in South Sumatera, namely Plaju, Musi Banyuasin District (104.78694°E, -2.98569°S), Jejawi, Ogan Komering Ilir/OKI District (104.79293°E, -3.06313°S), Kayu Agung, OKI District (104.80498°E, -3.32292°S), Teluk Gelam, OKI District (104.73877°E, -3.46498°S), and South Indralaya, Ogan Ilir District (104.64241°E, -3.26908°S), as shown in Figure 1. The undisturbed soils were taken with a ring sampler from a PVC pipe diameter 14 cm at a depth of 30 cm, according to standard sampling. Soil in the pipe are closed and wrapped in black plastic to avoid oxidation.

The factorial experiment was arranged in a completely randomized design replicated three times, with peaty soil samples from South Sumatera as the first factor treatment covering peaty soil from Plaju, Jejawi, Kayu Agung, Teluk Gelam, South Indralaya; and the application of steel slag as a second factor treatment consisting of without applying steel slag and with applying 1 mg steel slag/ha. Steel slag is broadcasted on peaty soil surface.

Peat taken from Plaju and Jejawi is a shallow peat (less than 50 cm depth) and categorized as peaty land that has been utilized for wetland cultivation, while that taken in Kayu Agung, Teluk Gelam and Indralaya is medium peat dominated by vegetation of *alang-alang*/cogon grass (*Imperata cylindrica* L.), *gelam* (*Maleleuca* sp.), and partly used for palm oil plantations.

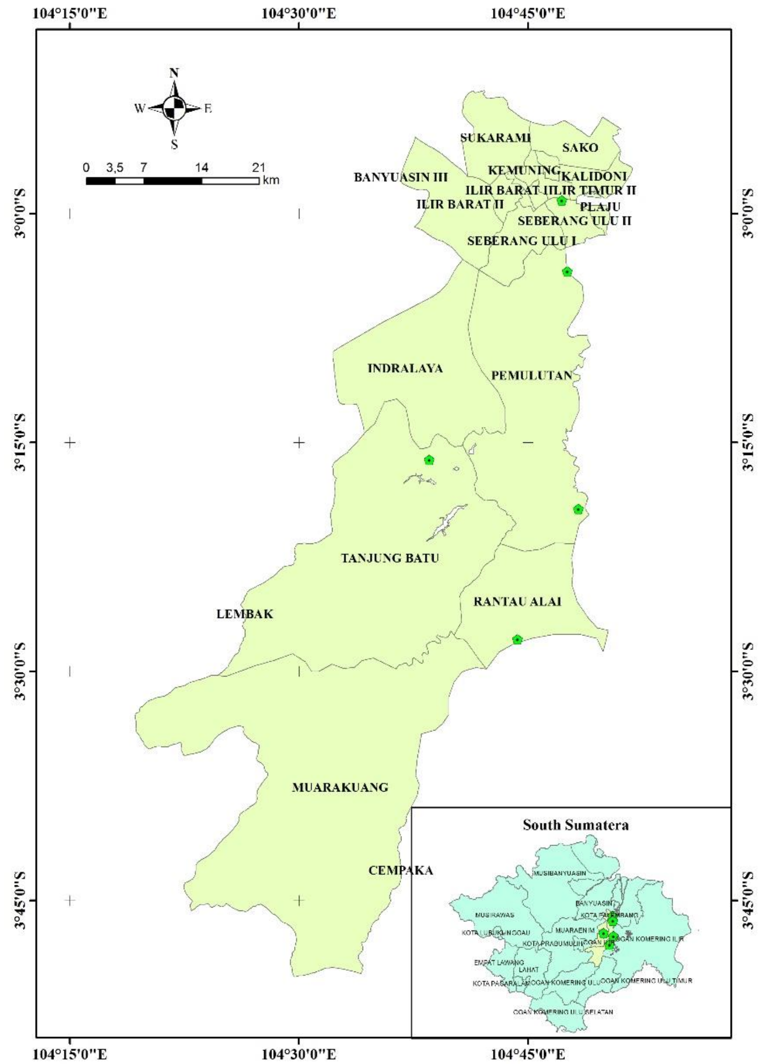

Figure 1. Map of peaty paddy soil sampling in South Sumatera

Characteristics of soil samples were analyzed at the Bogor Soil Research Institute Laboratory, while the analysis of GHG production rates was carried out in the GHG laboratory at Indonesian Agricultural Environment Research Institute. Analysis of physical and chemical properties of peaty soil covered fiber content, organic C (Walkley and Black method), total N (Kjeldahl method), available P (Bray 1 method), exchangeable K (Morgan method), cation exchangeable capacity and exchangeable cation (NH_4OAc 1 N saturation method), Al^{3+} and H^+ (KCl 1 N method), Fe, Mn, Cu, Zn (DTPA method), density (gravimetric method), fulvic, and humic acid content (extraction NaOH + $Na_2P_2O_7$ method).

2.2 Experimental implementation

Incubation was carried out in the laboratory. Peaty rice soils in PVC pipes were maintained in water saturation conditions and prepared for treatments. The top of the pipe was closed with a cover equipped with rubber septum, thermometer, and channel for gas N_2 intake. N_2 gas flowed at 250 mL/min into ring sampler, and gas samples were taken using a syringe vol-10 mL (t_0). After incubation for 24 h (t_{24}), the gas sample was taken again. Additional gas sampling was carried out every two days for 30 days with steps like the first step. Gas samples taken from the trap hood were injected in a gas chromatography (GC) device with different detectors. The CH_4 concentration was measured by a GC tool equipped with flame ionization detector (FID), while CO_2 concentration was analyzed using a GC tool with a thermal conductivity detector (TCD). The production rate of methane and carbon dioxide was determined using the equation used by Lantin et al. (1995), as follows:

$$E = (C_{24} - C_0) \times \frac{Vh}{20} \times \frac{mW}{mV} \times \frac{273.2}{(273.2+T)} \quad (1)$$

Where; E=production of CH_4 or CO_2 (mg/g soil); C_0=concentration of CH_4 or CO_2 at t_0 (ppm); C_{24}=concentration of CH_4 or CO_2 at 24 h after incubation (ppm); Vh=headspace volume in incubation glass (mL); mW=molecule weight of CH_4 or CO_2 (g); mV=molecule volume of CH_4 or CO_2 (22.4 L at standard temperature and pressure in mol/L); T=averaged temperature in incubator (°C)

2.3 Data analysis

The collected data were analyzed by analysis of variance using the SAS program followed by a real honest difference test (Tukey test) at 5% level to determine significant differences between treatments.

3. RESULTS AND DISCUSSION

3.1 Flux of methane and carbon dioxide

The highest methane flux is seen in peaty paddy soils from Kayu Agung compared to other locations (Figure 2). The lowest CH_4 flux was seen in peaty paddy soils from Indralaya followed by from Plaju, while the magnitude of methane flux on peaty soil from Gelam and Jejawi is between Indralaya/Plaju and Kayu Agung.

The application of slag can generally decrease methane production from peaty paddy soils, except in Teluk Gelam site (Figure 2). The decrease in CH_4 production is possible due to the oxidants role in steel slag such as Al_2O_3, SiO_2, CaO, MgO (Munir and Handayani, 2012), which can oxidate CH_4 to CO_2. Slags are rich in oxides of iron, aluminum, manganese, and silica that act as alternative electron acceptors in an anoxic soil and their application suppress CH_4 emissions by stimulating iron for reducing methanogenic bacterial activity (Das et al., 2019). Slag reduces potentially methane emission by 0.6-56.0% from rice fields, depend on the slag type, rate of application, soil type, and agronomic practices (Das et al., 2019). Amelioration of peaty paddy soils with steel slag produces flux with a range of 0.0002-0.0654 mg CH_4/g soil, while CH_4 production without applying steel slag ranges 0.0002-0.0787 mg/g soil during 55 days of incubation. The application of steel slag in anaerobic soil conditions does not affect the activity of methanogenic bacteria in the formation and release of methane gas.

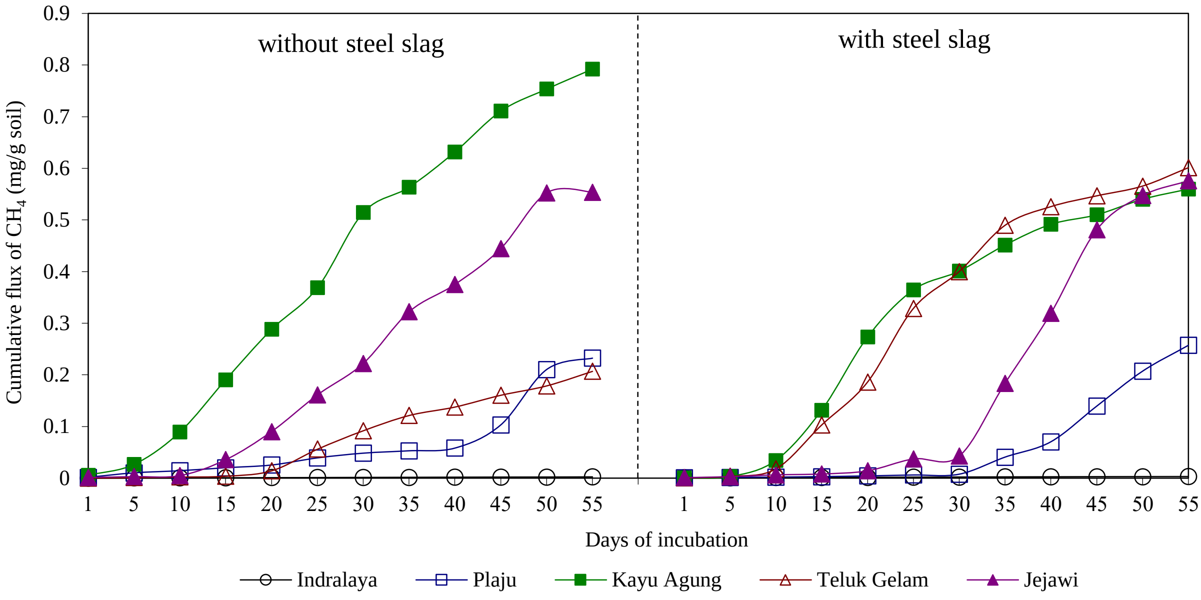

Figure 2. Cumulative fluxes of methane from peaty paddy soils in South Sumatra

The magnitude of methane production in peaty soils from Kayu Agung is related to peat condition that reacts rather acid-neutral, while the high flux in peat from Jejawi and Plaju may be due to the higher organic matter content (Table 1). The methane flux in peat from Indralaya is low during incubation which was caused by high soil acidity and oxidative condition that was more dominant than the reductive condition, so these conditions are not favourable for methanogenesis process.

Table 1. Characteristics of peaty paddy soil from South Sumatra

Site	$pH\text{-}H_2O$	C-total (g/kg)	N-total (%)	C/N	P_2O_5 HCl 25% (mg/ kg)	K_2O HCl 25% (mg/kg)	Exchangeable cations (cmol/kg)				CEC (cmol/kg)	BS (%)	Humic acid (g/kg)	Fulvic acid (g/kg)
							Ca	Mg	K	Na				
Indralaya	4.19	9.71	0.51	19	129	28	3.99	2.07	0.30	0.99	30.99	24	1.91	0.43
Plaju	5.12	11.17	0.72	16	19	14	3.96	3.49	0.18	1.56	31.04	30	2.56	0.51
Kayu Agung	5.65	6.80	0.49	14	34	49	3.43	1.70	0.25	0.29	19.70	29	1.41	0.68
Teluk Gelam	5.15	4.94	0.31	16	15	58	3.96	1.99	0.12	0.38	18.12	36	1.05	0.67
Jejawi	4.98	10.90	0.84	13	66	39	10.43	3.80	0.33	0.50	34.38	44	2.27	0.39

Note: CEC=cations exchange capacity, BS=base saturation

Peaty soil from South Sumatra generally reacts acid-slightly acid (pH>4), where the peaty pH value from Kayu Agung approaches neutral, while peaty from Indralaya reacts more acid than from Jejawi, Plaju, Teluk Gelam, and Kayu Agung (Table 1). The total C content of peat in South Sumatra is generally high. Peat from Teluk Gelam has the lowest total C content. Thin or shallow peaty soils from South Sumatra have generally been used for agricultural crops cultivation, so the organic material has been mineralized with a C N ratio less than 20. The content of P and K extracted with HCl 25% in South Sumatra peat ranges from 15-129 and 14-58 mg/kg, respectively. Exchangeable cations and cation exchange capacity (CEC) from Jejawi are relatively higher than from other sites. The magnitude of peaty CEC is possible due to more functional groups in organic matter. According to Liang et al. (2006), the oxidized functional groups in black carbon will increase cation exchange capacity in soils.

Figure 3 shows the fluctuations in production rate of CO_2 from South Sumatra peat. The lowest CO_2 flux was seen in peaty paddy soils from Indralaya followed by peat from Kayu Agung, while the highest CO_2 flux was seen in peaty rice soils from Plaju. Peat from Jejawi and Plaju has a thin layer with relatively high fulvic acid and humic acid content, so that the potential of mineralization rate is higher when soils cannot be maintained in its reductive conditions.

Peat contains functional groups such as carboxyls and phenols which are weak acids. The source of peat damage is caused by carboxyl and phenolic groups. Carbon emissions generally occur in aliphatic groups which are easily degraded by microbes to produce CO_2 and CH_4. The application of steel slag generally decreases CO_2 production from peaty wetlands (Figure 3). Steel slags contain oxides and polyvalent cations such as Al, Fe, Mn which can form coordination bonds with organic ligands where polyvalent cations form the core of coordination and bind monomeric organic acids to form complex compounds. Carboxyl functional groups are high in low pH peat. Applying slag can stabilize the bonds of organic acids and polyvalent cations and increase pH values (Husen and Agus, 2011). The oxidant contents of CaO, MgO, Al_2O_3, SiO_2 in steel slag enhances CO_2 production due to the oxidants role in oxidizing methane in peaty paddy soils. Amelioration of peat paddy soils with steel slag gives flux with a range of 2.17-3.42 mg CO_2/g soil, while CO_2 production without steel slag ranges from 1.99 to 4.64 mg/g soil for soil sample incubated for 70 days. Application of steel slag to peat wetlands significantly reduces the potential for CO_2 production. Addition of ameliorants that contain high valence cations may form a ligand complex with the simple organic acids and thus reduce the rate of peat decomposition (Husen and Agus, 2011).

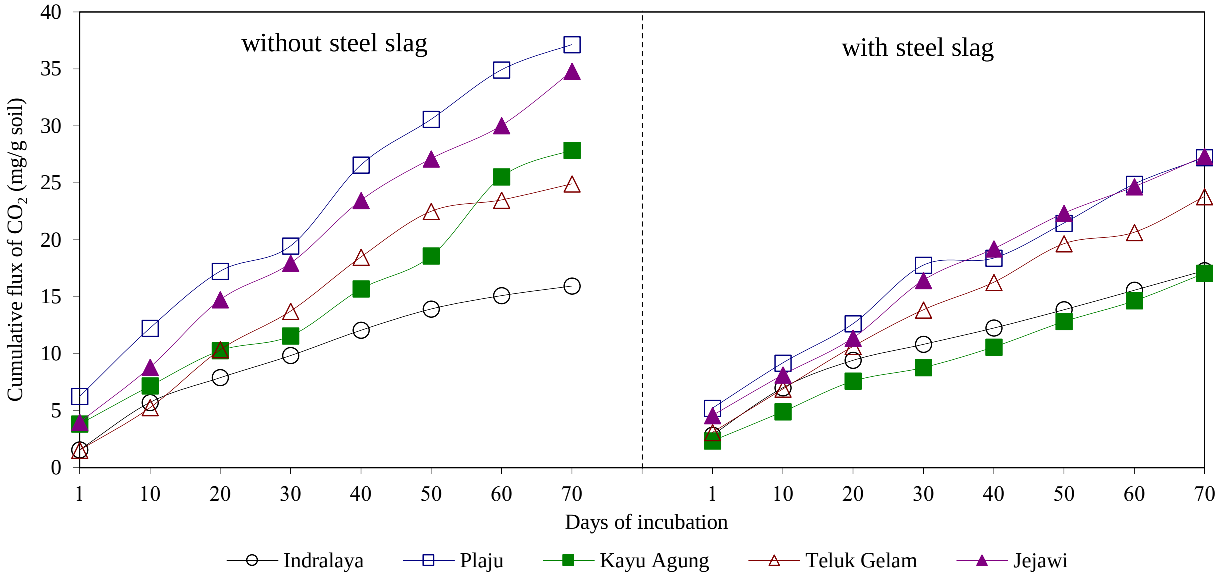

Figure 3. Cumulative flux of carbon dioxide from peaty paddy fields in South Sumatra

3.2 Production of methane and carbon dioxide

The low production of greenhouse gases (CO_2+CH_4) from Indralaya's peat paddy fields indicates that conversion of peat land to lowland rice cultivation has caused decomposition of organic matter which has resulted in a decrease in carbon availability in the peat soil. In peat soil from Plaju, CH_4 flux is low but CO_2 flux is high, this reflects that the peat soil is sensitive to aerobic conditions, so the decomposition process of organic matter will produce CH_4 higher than CO_2. In contrast, the peat soil from Kayu Agung shows high CH_4 flux and low CO_2 flux, this indicates organic matter decomposition under anaerobic conditions' potential to produce CH_4 higher than CO_2. It was also probable that the CH_4 was emitted from nonmicrobial sources of CH_4 production such as lignin and humic acids (Wang et al., 2013). This might have happened under tropical temperature as peat soils are high in organic matter besides being natural polyelectrolytes with substances such as humic and fulvic acids as its major components (Choo and Ahmed, 2017).

The potential for CH_4 and CO_2 productions from peaty paddy fields in the five locations in South Sumatra is significantly different with p value <0.05 (Table 2). The application of steel slag only significantly affects CO_2 production with p value of 0.0601 (Table 3). The application of steel slag into peat paddy fields tends to reduce the production rate of CH_4 and CO_2 after 70 days of incubation. The steel slag reduced production of CH_4 and CO_2 by an average of 19.24% and 18.95%, respectively. We presumed that the content of polyvalent cations in steel slag plays an important role in the complexation of organic acids which decreases production of CO_2 and CH_4 and increases soil pH.

Table 2. Potential production of greenhouse gas and acidity from five sites of peaty paddy fields in South Sumatra

Treatment	CH_4 flux (mg/g soil)	CO_2 flux (mg/g soil)	pH value
Indralaya	0.0002[a]	1.74[a]	3.80[a]
Plaju	0.0178[ab]	4.02[b]	4.29[a]
Kayu Agung	0.0657[b]	2.81[ab]	5.52[b]
Teluk Gelam	0.0257[ab]	3.05[ab]	5.15[b]
Jejawi	0.0574[ab]	3.88[b]	4.59[ab]
p value	0.0430	0.0068	0.0060

Means in same column followed by same letter are significantly different according to Tukey test at 0.05 level.

Table 3. Effect of steel slag application on production of methane, carbon dioxide and acidity of peaty paddy fields in South Sumatra

Treatment	CH_4 flux (mg/g soil)	CO_2 flux (mg/g soil)	pH value
Without steel slag	0.0369[a]	3.42[a]	4.12[a]
With steel slag	0.0298[a]	2.78[a]	5.22[b]
p value	0.4210	0.0621	0.0001

Means in same column followed by same letter are significantly different according to Tukey test at 0.05 level.

The average production of CO_2 in peat soils with steel slag applied ranged from 2.17-3.42 mg CO_2/g soil which is relatively lower than without steel slag application which ranged from 1.99-4.64 mg CO_2/g soil. With steel slag applied in peaty wetlands, the average of CH_4 production ranged between 0.0002-0.0501 mg CH_4/g soil, while without steel slag CH_4 production ranged between 0.0002-0.0660 mg CH_4/g soil. Generally, peaty paddy fields from Kayu Agung and Jejawi produced high CH_4 flux compared to the other three locations, while the highest CO_2 flux can be seen in Plaju and Jejawi locations. The lowest production of CO_2 and CH_4 is generally seen at the Indrajaya site.

3.3 Peat acidity

Peat has very low pH values, ranging from 3 to 4 depending on the peat properties. Peat requires additional lime such as calcitic or dolomitic lime to adjust the pH to a value around 5.5 (Prasad et al., 2020). Slag has been used widely in acidic soils to neutralize soil acidification (Das et al., 2019). Application of ameliorant on peat soil has an important role on improving fertility status of peat soil via increasing soil pH, reducing organic acids and toxic ions, and also increasing nutrients availability (Septiyana et al., 2016). The diversity of peat paddy fields significantly influences the soil acidity (p=0.006) as presented in Table 2. The application of steel slag also significantly determines the change in soil acidity (p=0.000), but its interaction with peat paddy fields does not significantly affect changes in soil pH. Thus, steel slag significantly decreases the acidity of peat paddy fields compared to without using steel slag. The pH values of peat without using steel slag ranged from 3.14-5.99 while pH values with steel slag ranged from 4.19-6.12. The average pH values of peatland without and with steel slag was 4.12 and 5.22, respectively. The slag fertilizer utilized in agriculture is effective to neutralize soil acidity (Das et al., 2019).

The content of Ca and Mg in steel slag plays a role in reducing soil acidity. Increased soil pH helps plants easily absorb other nutrients. There is a positive correlation between Ca and Mg and pH value. Slag application is not only to increase the pH value but also supply Ca and Mg which are essential plant nutrients required for plant growth (Prasad et al., 2020).

Steel slag has the opportunity and prospect to be used as fertilizer or ameliorant because of the essential cations needed for the growth and development of plants such as silicate, calcium, magnesia, iron, phosphor. Slag is high in lime, silicic acid, phosphoric acid, magnesia, manganese, and iron. The properties of the slag can be exploited to make use of fertilizer. Mostly in Japan, Korea, and China, slag has been intensively utilized as raw materials for fertilizer production, such as silicate fertilizer, lime fertilizer, slag and phosphate fertilizer to improve crop productivity, alleviate soil acidification, mitigate GHG emissions, and stabilize heavy metals (Das et al., 2019). The addition of slag-based silica fertilizer increase Si 0.16-47.2% in rice grain yield and could improve crop yield up to 47.2%. High yields in response to silicate fertilizer occurs because Si preferentially deposits in the epidermal cell wall and increase the physical strength of leaves and leaf-sheaths and helps plants to sustain yield by counteracting various biotic and abiotic stresses (Das et al., 2019).

Utilization of steel slag as fertilizer or ameliorant is constrained by its heavy metal content. Slags contain traces of heavy metals, but the concentrations of heavy metals might not be enough to pose environmental risks (Das et al., 2019). Before being applied on agriculture, the content of heavy metals in the fertilizer must be reduced to the permissible concentration based on regulations for hazardous heavy metals in order to be safe for the environment and human health.

4. CONCLUSION

Amelioration of peat paddy fields using steel slag tends to reduce the production rate of CO_2 and CH_4, and soil acidity. The application of steel slag reduced the production of CO_2 and CH_4 by 18.95 and 19.24%, respectively. The application of steel slag decreases production of CO_2 and CH_4 and increases soil pH. The potential production of methane from peaty paddy fields in South Sumatra, stated sequentially from the lowest, is Indralaya<Plaju< Teluk Gelam<Jejawi<Kayu Agung, while the potential for CO_2 production in peat rice fields is from Indralaya<Kayu Agung<Teluk Gelam<Jejawi<Plaju. Steel slag has the prospect to be utilized as a raw material of fertilizer or ameliorant to mitigate GHG emission from peaty soils and substitute for limestone to neutralize soil acidity and improve crop productivity.

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