Soil chemical properties affecting GHG emission from paddy rice field due to water regime and organic matter amendment

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Abstract. Paddy rice field is the main contributor of greenhouse gas (GHG) (CH4 and N2O) emissions in Indonesia. The actions to mitigate these emissions and maintain yield have been a serious concern. This study aims to investigate the emission of CH4 and N2O and determine the limiting factors of CH4 and N2O emission due to water regime and organic matter (OM) amendment in inceptisol soil. Treatments consist of two factors, the first factor was water regime, e.g., 1) continuously flooded, and 2) Alternate wetting-drying (AWD). The second factor was organic matter amendment, e.g., 1) with OM 3 t ha-1, and 2) without OM. The results showed that the addition of organic matter to the soils alongside managing its water regime with AWD resulted in low daily CH4 emissions compare to continuous flooded. No significant difference (p<0.05) in daily N2O emission between AWD and continuous flooded. The dynamic of C-organ, Eh, Fe2O3, MnO2 in the soil due to water regime were affected daily CH4 emissions, while pH, NO3 and NH4 were affected daily N2O emissions. Results of this study can be used for further research and development of a model on CH4 emission from rice fields to determine feasible soil management in GHG mitigation.

1. Introduction

Greenhouse gases like CH4 and N2O held an essential role in our atmosphere. In natural condition, they keep the earth in warm temperature which favors for livelihood. However, since mid of the 18th century, their concentration was increasing vigorously from levels of 722 and 270 ppb to present levels of 1,830 and 324 ppb [1]. They contribute for about 60% and 38% to the total GHG global emission, respectively [2]. The rapid increase of GHG emission related to human activities known as anthropogenic sources believed as a major caused of climate change. Action to reduce GHG emission in the atmosphere is a must to lower the impact of climate change.

Rice held an essential role for more than 50% of the human’s population. Studies about the forming process and its involving factor as well as how to reduce GHG emission from rice cultivation has been widely conducted [3][4]. Rice is a staple food in Indonesia. Rice cultivation especially in a flooded condition also known as the highest share of GHG emission in Indonesia. It is accounted for about 35% of the total emission from agriculture sector.

GHG emission from rice field is a complex interplay amongst climatic conditions, soil characteristic and field management techniques [5]. Soil microbial processes plays a vital role in generated greenhouse gases in the soil, but the amount of fluxes being emitted to the atmosphere depends heavily on soil physical and chemical factors [4]. Management practices such as water
management, soil tillage, fertilizer management were considered to influence GHG emissions. Flooding condition of rice field is the critical factor in methane (CH$_4$) production [6]. Organic matter decomposition in an anaerobic condition will produce CH$_4$ [7], while N$_2$O were produced through nitrification and denitrification [8]. A recent study in Indonesia proven that applying AWD could reduce CH$_4$ emission by 35% without reducing yield [9]. Alternate wetting-drying is an irrigation system to efficiently use the irrigation water, which also alter the methane production, therefore this irrigation system suggested as one of mitigation option from rice cultivation. However, the study about soil chemical properties involved in the emission process from rice field still lacks in Indonesia. The study aims to investigate the emission of CH$_4$ and N$_2$O and determine the limiting factors of CH$_4$ and N$_2$O emission due to water regime and organic matter (OM) amendment in inceptisol soil.

2. Materials and methods

2.1 Site description

The research was conducted at Indonesian Agricultural Environment Research Institute Research Station at Pati, Indonesia in dry season 2019 (April-June). The soil has 35% sand, 42% silt, 23% clay, pH (H$_2$O) 6.2, C-org (%) 0.63, N-tot (%) 0.07, CEC (Cmol(+)) kg$^{-1}$) 5.4, Fe (%) 0.64 and Mn (ppm) 40, it was classified as Inceptisol (Soil Taxonomy System USA). Pati located in an altitude ranges from 10 to 40 m above sea level, it has 30°C annual mean temperature, and annual rainfall were low which averages only 1503 mm and mostly falls in rainy season (oct-march). The same location as Setyantto P et. al [9].

2.2 Experimental design

Transplanting rice crops were established during the dry season. Full tillage (plowed and puddled thoroughly) were performed to the fields to a 10-cm soil depth at 5 days before rice transplanting. After 21 days, Ciherang rice seeds were removed from the seed-bed and transplanted onto each plot. The plot size was 5x4 m. Rice seeds were transplanted one seedling per hill into each plot, with 20x20 cm plant spacing. A randomized factorial block design was used to arranged the experimental plot. Treatments consist of two factors, the first factor was water regime, e.g., 1) continuously flooded (CF), and 2) Alternate wetting-drying (AWD). The second factor was organic matter amendment, e.g., 1) with Organic Matter (OM) 3 t ha$^{-1}$, and 2) without OM. The AWD plots arrangements were as describe by Setyanto P et. al [9] and fertilization as describe by Ariani M et. al [10].

2.3 Gas sampling and measurement

A static closed chamber method and gas chromatography techniques were used to measure the CH$_4$ and N$_2$O fluxes [11]. Gas samples were collected weekly, but in this paper, we only consider the gas samples at 7, 42 and 63 DAT (days after transplanting) following the soil samples. Twenty (20) ml plastic syringes which equipped with a three-way stopcock were used to collect the gas samples. It is taken at 0, 10, 20 and 30 min after the chamber was closed and then filled into 10 ml vacated glass vial. The samples were transferred immediately to the laboratory to analyzed the gas concentrations using a gas chromatograph (Varian GHG 450 Series equipped with a flame ionization detector (FID) for CH$_4$ an an electron capture detector (ECD) for N$_2$O) which work simultaneously. The gas flux calculation methods were the same as those used by IAEA (1992):

$$E = \frac{Bm}{Vm} \frac{\Delta C}{\Delta t} \frac{V}{A} \frac{273.2}{T + 273.2}$$

where $E$ is CH$_4$/N$_2$O flux (mg m$^{-2}$ min$^{-1}$), Bm is molecular weight of CH$_4$/N$_2$O (g), Vm is molecular volume of CH$_4$/N$_2$O at standard temperature and pressure (22,411), $\Delta C/\Delta t$ is changes of CH$_4$/N$_2$O concentration over time (ppm min$^{-1}$), V is chamber volume (m$^3$), A is chamber area (m$^2$) and T is mean air temperature inside the chamber during gas sampling (°C). CH$_4$/N$_2$O flux was determined
based on the CH$_4$/N$_2$O concentration rate change during a period of chamber closure, which was estimated as the slope of a linear regression between concentration and time.

2.4 Soil sampling and analyses
Fresh soil samples (0-20 cm) were taken from the field, it was taken 2 days before transplanting, 42 days after transplanting (DAT) and 63 DAT. We consider to measure soil chemical properties after the soil were experience the wet and dry period for several times. We collected three sub samples from each plot, mixed into one soil sample, and placed in dry sample bags after manually remove of any plant residue and roots. Soil samples were analyzed for total N (Kjeldahl method), total C (Spectrophotography), Fe$_2$O$_3$ (Atomic Absorption Spectroscopy/AAS), MnO$_4$ (Atomic Absorption Spectroscopy/AAS), NH$_4$, NO$_3$.

2.5 Additional measurement
Soil redox potential (Eh), pH and temperature were measure at the same time of gas measurement. Soil water table was measure every day.

2.6 Statistical analysis
Statistical software Minitab 16 version was used to analyze the effect of different treatments. A two-way analysis of variance (ANOVA) was performed to examine the significant effects of the treatment. When significant differences were detected at $P=0.01$ and $P=0.05$, the mean values were compared by using Tukey’s pairwise comparison test. The correlation between soil properties and GHG daily emissions were perform using Ms. Excel 2010.

3. Result and discussion
3.1 CH$_4$ and N$_2$O daily flux
The pattern of daily CH$_4$ and N$_2$O emissions from rice field as affected by water management and organic matter amendment were shown in Fig. 1. There was a trend of a trade-off between CH$_4$ and N$_2$O flux. Methane flux from CF+OM showed the highest among other treatment, and this was fully acknowledged as there was a high carbon substrate in an anaerobic condition. This condition was favorable for CH$_4$ production in rice field [12]. The lowest amount of CH$_4$ daily flux showed from AWD+No OM plot. Methane fluxes from all treatments were peaking on 42 DAT and tend to decrease during 63 DAT, this was assumed to be related to rice plant growth phase. Rice plant growth phase were one of the crucial elements determining the amount of CH$_4$ production. During the beginning of vegetative phase, the emission is negligible, gradually rising during late of vegetative phase, experiencing a peak near panicle differentiation, relatively constant during reproductive phase and decreasing during late grain [13]. A field study in Vietnam on different water management and organic matter amendment showed a similar result [14]. N$_2$O daily emissions were relatively similar among all treatments. Daily CH$_4$ emissions from AWD was significantly lower than CF ($p<0.05$, n=48), but there was no significance different in daily N$_2$O emission between treatments.
Figure 1. CH$_4$ and N$_2$O daily fluxes under water management and organic matter amendment treatments in Inceptisol Soil, Jakenan DS 2019

3.2 Relationship between CH$_4$ daily emissions and soil chemical properties

Soil chemical properties were examined at two days before transplanting as the original content, and then at 42 and 63 DAT, when the soil has experienced a few cycles of wetting and drying for the AWD treatment. The relationship between GHG daily emission and soil chemical properties were divided based on the water regime in Fig. 2. Iron content (Fe$_2$O$_3$) was negatively correlated with CH$_4$ daily emission in both water regimes, significantly correlated when the soil was in continuously flooded condition according to this measurement (p<0.05, n=16). The same result also showed for manganese (MnO$_4$). Previous research from a laboratory measurement has confirmed the same [15], but another study resulted otherwise [16].

When soil is submerged by water, free gas exchange between soil-air and the atmosphere is inhibited. Thus, when oxygen is limited in the soil, some of the chemical properties such as Fe$^{3+}$, Mn$^{4+}$ and NO$_3^-$ were reduced [17]. These chemical properties play a role as the electron acceptors in sequential order after the soil was in flooded condition. After the soil was flooded and O$_2$ slowly disappeared, the facultative anaerobic bacteria will use the available electron acceptors [15], explaining the negative correlation between Fe$_2$O$_3$ and MnO$_4$ with CH$_4$ emission.

Carbon content in the soil is positively correlated with CH$_4$ emission in continuously flooding (p<0.01, n=16) and AWD (p<0.05, n=16). Organic substrates serve as a source of electrons for the formation of CH$_4$ through reductive processes. Setyanto P et. al [15] and Wihardjaka A and Harsanti ES [16] confirmed it with an addition of organic substrate to the soil in an incubation experiment. The CH$_4$ production potential was increase from 2 until 12 fold for every soil types in the experiment.

Potential redox (Eh) were negatively correlated with the CH$_4$ emissions in CF (p<0.05, n=16) and AWD (p<0.01, n=16). Methane flux will release in a low potential redox [17]. CH$_4$ emissions and production will increase when soil conditions reach a potential redox <-150 mV and high soil pH (6-7) [18]. The lowest Eh from CF reached the value of -170 mV which resulted in highest CH$_4$ emission as well (680 mg CH$_4$ m$^{-2}$ d$^{-1}$). Redox is the transformation of the chemical properties with two or more valence states. When the soil is submerged, the Eh value will slowly decrease to reduction state.
3.3 Relationship between \( \text{N}_2\text{O} \) daily emissions and soil chemical properties

Nitrous oxide (\( \text{N}_2\text{O} \)) emission were negatively correlated with \( \text{NO}_3^- \) and \( \text{NH}_4^+ \) in AWD treatment (\( p<0.05, \ n=16 \)) and with \( \text{NO}_3^- \) in CF (\( p<0.05, \ n=16 \)). \( \text{NH}_4^+ \) and \( \text{NO}_3^- \) were two soil N mineral which responsible for the process of nitrification-denitrification. In an aerobic condition, \( \text{NH}_4^+ \) will be oxidized to \( \text{NO}_3^- \) by chemoautotrophic bacteria and release \( \text{N}_2\text{O} \), while in an anaerobic condition, \( \text{NO}_3^- \) will reduced to \( \text{N}_2 \) by anaerobic bacteria and release \( \text{N}_2\text{O} \) [19]. Significance decrease of these ions, will resulted in increasing \( \text{N}_2\text{O} \) emission [5]. There is no significant correlation between \( \text{NH}_4^+ \) and \( \text{N}_2\text{O} \) daily emission under CF, this was probably due to the effect of air availability in the soil. Denitrification is likely more dominated due to the flooded condition which causes a high of water-filled pore space (WFPS). High WFPS (80%) in soil is a favorable condition for the formation of \( \text{N}_2\text{O} \) [20]. In a condition of higher WFPS (>70%) denitrification plays the main source of \( \text{N}_2\text{O} \) formation, and when it decreases to 60%, nitrification plays the main source [21].

**Figure 2.** Correlation between \( \text{CH}_4 \) daily flux and soil chemical properties (C-org, \( \text{Fe}_2\text{O}_3 \), \( \text{Eh} \), \( \text{MnO}_4^- \)) under a) continuous flooding and b) AWD treatment.
The nitrification-denitrification processes are managed by many environmental elements, the most crucial are: temperature, pH and soil water content [22]. Nitrous oxide emission under AWD was positively correlated with pH (p<0.05, n=16), but not under CF. In a condition of low pH with the presence of abundant O₂, nitrous oxide reductase is inhibited. Higher pH level will lower N₂O emissions from soil in a condition where denitrification is the primary source of N₂O production. In contrary, if nitrification is the primary source, an increase of soil pH stimulates the N₂O production [23]. N₂O emission would be higher in the soil with low pH values, because only a little of this gas will be reduced to N₂ [24]. Excessive use of synthetic fertilizer will bring the soil to an acid condition which will lead to enhancement of N₂O emission. Soil in acid condition could be adjusted to a higher pH to reduced emission through the use of liming.

4. Conclusion
Methane and nitrous oxide emission from rice field is the major contributor of GHG emission from agriculture sector in Indonesia. This emission is a complex interplay amongst climatic conditions, soil characteristic and soil management techniques. The addition of organic matter to the soils alongside managing its water regime with AWD resulted in low daily CH₄ emissions compare to continuous flooded. No significant difference (p<0.05) in daily N₂O emission between AWD and continuous flooded. The dynamic of C-org, Eh, Fe₂O₃, MnO₂ in the soil due to water regime affected daily CH₄ emissions, while pH, NO₃ and NH₄ affected daily N₂O emissions. More soil chemical properties e.g soil moisture, soil porosity, WFPS, etc, soil physical properties and soil microbial processes needs to be examine as well for better understanding of GHG production and emission.
Acknowledgement
MIRSA III Project under the Paddy Rice Research Group of Global Research Alliance funded the field research, and Gadjah Mada University under the research grant for Thesis recognition 2019 funded measurements of soil sampling.

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