SOIL CONTROLLING FACTORS OF METHANE GAS PRODUCTION FROM FLOODED RICE FIELDS IN PATI DISTRICT, CENTRAL JAVA

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ABSTRACT

Atmospheric methane (CH\textsubscript{4}) is recognized as one of the most important greenhouse gases. Methane, with some 15-30 times greater infrared-absorbing capability than CO\textsubscript{2} on a mass basis, may account for 20% of anticipated global warming. Soils are one of the key factors, which play an important role in CH\textsubscript{4} production and emission. However, data on CH\textsubscript{4} emission from different soil types and the characteristics affecting CH\textsubscript{4} production are lacking when compared to data on agronomic practices. This study was conducted to investigate the potential of CH\textsubscript{4} production of selected soils in Java, and determine the limiting factors of CH\textsubscript{4} production. The results showed that addition of 1\% glucose to the soils led to an increase in CH\textsubscript{4} production by more than twelve fold compared to no glucose addition. The CH\textsubscript{4} production potential ranged between 3.21 and 112.30 mg CH\textsubscript{4} kg\textsuperscript{-1} soil. The lowest CH\textsubscript{4} production potential occurred in brown-grayish Grumosol, while the highest was in dark-gray Grumosol. Chemical and physical properties of the soils have great influence on CH\textsubscript{4} production. Stepwise multiple regression analysis of CH\textsubscript{4} production and soil characteristics showed that pH and the contents of Fe\textsubscript{2}O\textsubscript{3}, MnO\textsubscript{2}, SO\textsubscript{4}, and silt in the soil strongly influenced CH\textsubscript{4} production. Results of this study can be used for further development of a model on CH\textsubscript{4} emission from rice fields.

[Keywords: methane, rice fields, soil chemophysical properties, Central Java]

INTRODUCTION

Methane (CH\textsubscript{4}) is one of the important greenhouse gases in the atmosphere (Dlugokencky \textit{et al.}, 1994). Without the presence of the greenhouse gases, the air temperature of the earth's surface would be 2-3 times lower than the actual temperature we experience now. The increase of CH\textsubscript{4} in the atmosphere contributes to global warming and affects the chemical changes in the atmosphere (Cicerone and Oremland, 1988; GEIA, 1993; Khalil and Shearer, 1993; IPCC, 1996). Rice fields are one of the major CH\textsubscript{4} sources (Cicerone and Shetter, 1981; Sass \textit{et al.}, 1990; Rennenberg \textit{et al.}, 1992; Neue and Roger, 1994; Wassmann \textit{et al.}, 1995; Neue and Sass, 1998; Wassmann \textit{et al.}, 1998). The rice paddy environment, e.g., soil, water, and the rice plant, is actively implicated in CH\textsubscript{4} production, oxidation, and transportation (Seiler \textit{et al.}, 1984; Holzapfel-Pschorn \textit{et al.}, 1985; Schultz and Seiler, 1989; Neue \textit{et al.}, 1997).

Methane production and oxidation in flooded rice soils are regulated by various microorganisms, which are controlled by biological, chemical, and physical factors of the soil environment. The rhizosphere of rice plants will affect both production and oxidation of CH\textsubscript{4}. During the growth of rice plants, soil environmental conditions fluctuate due to changes in floodwater level, temperature, root growth, and fertilizer. In such a dynamic system, it is important to understand the factors which control CH\textsubscript{4} emission to the atmosphere. Soils are one of the key factors which play an important role in CH\textsubscript{4} production and emission. However, data on CH\textsubscript{4} emission from different soil types and the characteristics affecting CH\textsubscript{4} production are lacking when compared to data on agronomic practices.

Since the first study of CH\textsubscript{4} emission from a Californian rice field by Cicerone and Shetter (1981), evidence has accumulated showing that climate, organic matter amendment, water regime, rice variety, and fertilizer influence CH\textsubscript{4} emission from rice fields. Research on CH\textsubscript{4} emission in relation to these factors has been conducted extensively in some countries, i.e., the Philippines, China, United States, Japan, India, Thailand, and the Netherlands. However, data on CH\textsubscript{4} fluxes from different soil types and the soil characteristics controlling the production of CH\textsubscript{4} are still lacking. This study is important in terms of developing a model to predict CH\textsubscript{4} emission from rice.
fields. Understanding the controlling factors on CH$_4$ production would facilitate developing such a model. Therefore, this study was conducted to investigate the potential of CH$_4$ production of selected soils in Java and to determine the soil characteristics controlling the emission.

**MATERIALS AND METHODS**

Laboratory experiment to determine the potential production of CH$_4$ from rice field soils was conducted. Eleven types of rice soils were selected from irrigated wetland areas in Pati, Central Java. The soils were collected based on the Indonesian Center for Soil and Agroclimate Research and Development (ICSARD) Soil Maps developed by Soepraptohardjo and Suwardjo (1966). Soil samples were classified based on the FAO Soil Classification. Eleven soil types identified from Pati District are brown Regosol, red Latosol, dark-brown Alluvial, gray-yellowish Alluvial, brown Latosol, gray Hydromorph Association, dark-gray Grumosol, brown-reddish Mediterranean, dark-brown Mediterranean, dark-gray Grumosol and Lithosol Association, and brown-grayish Grumosol.

Soils were randomly collected from 0-20 cm depths soon after rice crops were harvested. The soil samples collected were used to measure the potential production of CH$_4$ from their original organic matter sources. The soils were also treated with a reducible C-source, i.e., glucose (C$_6$H$_{12}$O$_6$) to enhance their CH$_4$ production capacity and observations made on whether the initial characteristics of the soils could affect the production of CH$_4$. Glucose was added to the soils to ensure that carbon was not limiting in the soils.

**Incubation Technique**

Twenty-gram samples (air dried) of each soil type were placed in bottles of 120-ml volume. The incubation bottles consisted of glass beaker with a rubber stopper. The syringe holes for gas collection and pH/Eh electrode were arranged in series through two small holes in the stopper. The two small holes were also used to insert nitrogen gas to the headspace. Gas samples were withdrawn every 4 days and pH and Eh were recorded. To ensure maximum CH$_4$ production, a reducible C-source, i.e., glucose was added to all the soils; 1% of C over the weight of the soil used for incubation. In this way, the influence of soil characteristics on CH$_4$ production could be better observed. This is important if we want to determine the soil characteristics that control CH$_4$ production because not all soils contain sufficient carbon source.

All bottles were incubated anaerobically at 25°C for approximately 52 days to allow maximum process for methanogenic bacteria to produce CH$_4$. Distilled water (50 ml per bottle) was added to flood the soil and the bottle was tightly stoppered, therefore, there was an empty headspace of 70 ml in the bottle in which CH$_4$ and other gases produced during the incubation accumulated. To avoid contamination of the headspace from ambient CH$_4$, the empty headspace was first saturated with a CH$_4$-free gas of ultra-high purity (99.99% nitrogen gas) one day before a gas sample was collected.

The experiment was conducted in four series, each consisting of three soil types with four replications, with and without glucose treatment. Therefore, in total there were 24 bottles for this study.

**Assessment of CH$_4$ Production**

To ensure the release of all CH$_4$ produced during sampling, a magnetic stir bar was inserted in the middle of the soil surface in each bottle before the bottles were stoppered. The bottle was stirred and flushed with N$_2$ for 2 minutes at a flow rate of 200 ml minute$^{-1}$. At this time, CH$_4$ produced in the headspace was released and collected using a 5-ml syringe. This was considered as C$_0$ (concentration of CH$_4$ at time 0). For production rate measurement, 24 hours after taking C$_0$, the bottles were stirred again for 2 minutes and a 5-ml gas sample was withdrawn from the headspace (the headspace gas was mixed thoroughly by pushing the syringe plunger up and down at least 10 times). This was considered as C$_{24}$ (concentration of CH$_4$ after 24 hours of incubation).

The differences in concentration between C$_{24}$ and C$_0$ was regarded as the CH$_4$ production rate per day. After sampling for C$_{24}$ concentration, the bottle was again flushed with N$_2$ while stirring for 2 minutes, and then the incubation processes were continued. Gas samples were collected every 4 days until 52 days of incubation. Methane concentration was analyzed using gas chromatograph (GC) equipped with a flame ionization detector (FID) and a porapak N column of 3m 80/100 mesh. The GC conditions were: (1) carrier gas flow of N$_2$ 30 ml minute$^{-1}$, (2) 5 bars of compressed air and hydrogen pressure, (3) temperature of injection port 80°C, and (4) column temperature 110°C. A standard of 10.1 ppm of CH$_4$ was regularly analyzed through the GC.

Methane production rate was determined using the following equation (Lantin et al., 1995):

$$\text{Methane production rate} = \frac{C_{24} - C_0}{24}$$
Soil controlling factors of methane production from flooded rice fields

Wang et al. (1993a) and Neue et al. (1994). The soils were grouped based on their capacity to produce CH$_4$. Wang et al. (1993a) mentioned that the production of CH$_4$ is related to soil texture, reducible iron, manganese oxides, sulfates, and organic compounds. These properties affect the redox potential, which afterwards may influence the production of CH$_4$ by methanogenic bacteria.

Adding 1% C-glucose to the soils increased CH$_4$ production by at least 12 times compared with the untreated soils (Fig. 2). The dark-gray Grumosol soil produced the highest CH$_4$ level, while the brown-grayish Grumosol was the lowest. Methane production from the gray Hydromorph Association showed a different pattern with very high production of CH$_4$ without glucose addition, which dropped following the addition of glucose. This phenomenon on the gray Hydromorph Association was unclear, but it might be due to a sudden drop of pH of the soil on glucose treatment (Fig. 3). The pH drop ranged between 3.5 and 4.0, which was probably due to the accumulation of hydrogen ion from the reduction of glucose in the anaerobic condition. Methanogenic bacteria actively produce CH$_4$ at pH 6-7 and this drop of pH could reduce the methanogenic activity drastically. A similar result was also obtained by Morgan (1968), who showed that in a laboratory experiment, CH$_4$ formation dropped after 1% organic matter was added to an acidic soil. He mentioned that large amount of acetic acid and smaller amount of propionic and n-butyric acids probably resulted during incubation in anaerobic condition, which leads to the drop of soil pH.

Figure 2 shows that most of the soils analyzed produced more CH$_4$ on glucose treatment. The CH$_4$ production potentials of the soils were divided into three categories, low (3.21-10.15 mg CH$_4$ kg$^{-1}$ soil), medium (22.51-61.08 mg CH$_4$ kg$^{-1}$ soil), and high (86.28-112.3 mg CH$_4$ kg$^{-1}$ soil). These categories were based on the statistical analyses through comparing the means of the total CH$_4$ produced and analyzing the differences using Duncan’s Multiple Range Test. Total CH$_4$ production during 52 days of incubation was shown in Table 2. Without addition of glucose to the soil samples, the dark-gray Grumosol gave the lowest CH$_4$ production (0.19 mg CH$_4$ kg$^{-1}$ soil), and after addition of glucose it produced the highest (112.3 mg CH$_4$ kg$^{-1}$ soil). Before glucose was added, the CH$_4$ production pattern of the dark-gray Grumosol was flat. The same results were obtained on the dark-brown Mediterranean, brown Regosol, and brown-reddish Mediterranean. However, after glucose was added, the brown Regosol and dark-brown

$$E = \frac{(C_{24} - C_0) \times \frac{V_h \times mW}{20 \text{ g}} \times \frac{273.2}{mV} \times (273.2 + T)}{(273.2 + T)}$$

$E$: CH$_4$ production (mg kg$^{-1}$ soil day$^{-1}$)
$C_0$: CH$_4$ concentration in time 0 (ppm)
$C_{24}$: CH$_4$ concentration after 24 hours (ppm)
$V_h$: Volume of headspace in incubation bottles (ml)
$mW$: Molecular weight of CH$_4$ (g)
$mV$: Molecular volume of CH$_4$ (22.41 liter at standard temperature and pressure/stp)
$T$: Temperature of incubator (°C)

Chemical and Physical Analyses of the Soils

The chemical properties analyzed were total-N, P, K, Fe$_2$O$_3$, MnO$_2$, total-C, Ca, Mg, Na, Mn, Cu, Zn, extractable S, total-S, and CEC, whereas the physical properties were texture and bulk density of the soil, before the incubation experiment started. The soil analyses were carried out at the ICSARD, Bogor. The soils were collected randomly from ten points in every location, and mixed thoroughly to obtain composite soil sample. Results of the soil analyses are given in Table 1. Data obtained were analyzed using stepwise multiple regression (Snedecor, 1946) to determine relationship between soil properties and CH$_4$ production.

RESULTS AND DISCUSSION

Methane Production Potential of Various Soil Orders

The capacity of the 11 soils to produce CH$_4$ from its indigenous carbon source varied, and they are grouped in low, medium, and high categories. The patterns of CH$_4$ production from each soil during the incubation periods are given in Fig. 1. Gray-yellowish Alluvial and gray Hydromorph Association were grouped as the highest CH$_4$ production capacity with the total CH$_4$ production of 7.75 and 37.66 mg CH$_4$ kg$^{-1}$ soil, respectively. Soils categorized as brown-grayish Grumosol, red Latosol, dark-gray Grumosol and Lithosol Association, brown Latosol, and dark-brown Alluvial were grouped as medium CH$_4$ production capacity ranging between 0.44 and 2.54 mg CH$_4$ kg$^{-1}$ soil. The dark-gray Grumosol, dark-brown Mediterranean, brown Regosol, and brown-reddish Mediterranean were grouped as low production capacity ranging between 0.19 and 0.28 mg CH$_4$ kg$^{-1}$ soil within the 52-day period.

Grouping the soils according to their capacity to produce CH$_4$ was also introduced by Wang et al. (1993a) and Neue et al. (1994). The soils were grouped based on their capacity to produce CH$_4$. Wang et al. (1993a) mentioned that the production of CH$_4$ is related to soil texture, reducible iron, manganese oxides, sulfates, and organic compounds. These properties affect the redox potential, which afterwards may influence the production of CH$_4$ by methanogenic bacteria.
Table 1. Physical and chemical properties of soils in Pati District, Central Java.

| Location          | Soil classification (FAO) | Texture (%) | Organic matter | Extrait. HCl 25% | Citrate-dithionite | Oxalate | Extrac. DTPA |
|-------------------|---------------------------|-------------|----------------|------------------|-------------------|---------|--------------|
|                   |                           | Sand        | Silt           | Clay             | P_2O_5            | K_2O    | MnO_2        | Fe_2O_3 | Mn  | Cu  | Zn  |
| Dukuhseti         | Brown Regosol             | 52          | 34             | 14               | 0.57              | 0.07    | 9           | 329     | 46  | 0.19| 1.24| 289 | 1.5 | 1.2 |
| Muktiharjo        | Red Latosol               | 3           | 30             | 67               | 0.52              | 0.04    | 12          | 119     | 87  | 5.72| 0.21| 0.94| 90  | 0.6 | 0.1 |
| Pantirejo         | Dark-brown Alluvial       | 2           | 38             | 60               | 2.01              | 0.15    | 13          | 50      | 33  | 2.09| 0.02| 1.09| 46  | 3.1 | 1.0 |
| Dukuh Mulyo       | Gray-yellowish Alluvial   | 8           | 71             | 21               | 1.49              | 0.15    | 10          | 94      | 35  | 2.16| 0.04| 0.51| 33  | 3.8 | 1.9 |
| Jrahi             | Brown Latosol             | 5           | 58             | 37               | 1.62              | 0.15    | 11          | 197     | 22  | 4.76| 0.19| 2.03| 199 | 3.1 | 1.3 |
| Plosorejo         | Gray Hydromorph Association & brown-grayish Planosol | 17          | 68             | 15               | 1.07              | 0.11    | 10          | 26      | 3   | 0.31| 0.01| 0.25| 14  | 0.8 | 0.7 |
| Ngurenrejo        | Dark-gray Grumosol        | 14          | 65             | 21               | 0.71              | 0.06    | 12          | 330     | 88  | 2.33| 0.19| 0.88| 273 | 8.4 | 1.5 |
| Purwokerto        | Brown-reddish Mediterranean and Lithosol Association | 5           | 72             | 23               | 1.47              | 0.14    | 11          | 35      | 33  | 3.15| 0.10| 0.40| 198 | 3.9 | 1.5 |
| Wonorejo          | Dark-brown Mediterranean Association | 7           | 54             | 39               | 1.43              | 0.12    | 12          | 312     | 56  | 4.92| 0.31| 2.17| 237 | 5.3 | 1.5 |
| Banyu Urip        | Dark-gray Grumosol and Lithosol Association | 6           | 47             | 47               | 1.46              | 0.15    | 10          | 124     | 107 | 4.69| 0.29| 1.20| 132 | 0.8 | 0.6 |
| Treteg            | Brown-grayish Grumosol Association | 17          | 48             | 35               | 0.85              | 0.08    | 11          | 18      | 6   | 1.46| 0.04| 0.41| 117 | 1.7 | 0.9 |

Table 1. Continued

| Location          | Soil classification (FAO) | SO_4 (ppm) | Extract. NH_4-acetate | 1 N | pH 7 | pH | Base Density sat. (g cm^(-3)) | Density (%) |
|-------------------|---------------------------|------------|-----------------------|-----|------|----|-------------------------------|--------------|
|                   |                           | Total KCl  | Ca                    | Mg  | K    | Na | CEC                          | H_2O KCl     |               |
|                   |                           | 0.25 N     |                       |     |      |    |                              |              |               |
| Dukuhseti         | Brown Regosol             | 478        | 54                    | 11.18| 3.87| 0.10| 0.50                        | 14.39        | 6.61 | 5.41| 100 | 1.56 |
| Muktiharjo        | Red Latosol               | 268        | 32                    | 11.05| 3.92| 0.51| 0.63                        | 21.10        | 5.78 | 4.45| 76  | 1.29 |
| Pantirejo         | Dark-brown Alluvial       | 1950       | 178                   | 18.29| 10.60| 0.32| 0.73                        | 37.14        | 6.33 | 5.38| 81  | 1.69 |
| Dukuh Mulyo       | Gray-yellowish Alluvial   | 1582       | 227                   | 17.82| 9.18| 0.24| 0.57                        | 33.52        | 7.52 | 6.70| 83  | 1.67 |
| Jrahi             | Brown Latosol             | 644        | 29                    | 6.15 | 2.23| 0.24| 0.37                        | 11.86        | 5.44 | 4.40| 76  | 1.44 |
| Plosorejo         | Gray-Hydromorph Association & brown-grayish Planosol | 537       | 32                    | 3.03 | 0.69| 0.06| 0.13                        | 6.82         | 4.53 | 3.66| 57  | 1.51 |
| Ngurenrejo        | Dark-gray Grumosol        | 509        | 61                    | 15.90| 5.59| 0.37| 0.74                        | 20.75        | 6.33 | 6.02| 100 | 1.56 |
| Purwokerto        | Brown-reddish Mediterranean and Lithosol Association | 739       | 32                    | 18.83| 2.49| 0.31| 0.24                        | 23.04        | 7.15 | 5.99| 95  | 1.76 |
| Wonorejo          | Dark-brown Mediterranean Association | 563       | 68                    | 14.45| 4.34| 0.17| 0.39                        | 14.32        | 5.59 | 4.67| 100 | 1.60 |
| Banyu Urip        | Dark-gray Grumosol and Lithosol Association | 1050      | 118                   | 8.36 | 2.66| 1.11| 0.13                        | 17.97        | 5.03 | 4.16| 68  | 1.49 |
| Treteg            | Brown-grayish Grumosol Association | 262       | 32                    | 18.38| 1.61| 0.16| 0.62                        | 18.05        | 6.58 | 5.41| 100 | 1.78 |

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Fig. 1. Methane production pattern of the soils without addition of C-glucose during 52 days of incubation. The production pattern is divided into three groups: (a) low, (b) medium, and (c) high production of $\text{CH}_4$. 

- **Fig. 1a**: 
  - **Dark-gray Grumosol**
  - **Dark-brown Mediterranean**
  - **Brown Regosol**
  - **Brown-reddish Mediterranean**

- **Fig. 1b**: 
  - **Brown-grayish Grumosol**
  - **Red Latosol**
  - **Dark-gray Grumosol and Lithosol Association**
  - **Brown Latosol**
  - **Dark-brown Alluvial**

- **Fig. 1c**: 
  - **Gray-yellowish Alluvial**
  - **Gray Hydromorph Assoc.**
Fig. 2. Methane production pattern of the soils with addition of C-glucose during 52 days of incubation. The production pattern is divided into three groups: (a) low, (b) medium, and (c) high production of CH$_4$. 

[Graphs showing CH$_4$ production over incubation period for different soil types]
Fig. 3. pH changes of the 11 soils treated with and without C-glucose. The pH changes of the soils were recorded every 4 days for 52 days of incubation.
Mediterranean exhibited an increase in CH₄ production. Methane production rate of these two soils ranged between 50 and 90 mg CH₄ kg⁻¹ soil. Brown-reddish Mediterranean seems to have low CH₄ production potential even when glucose was added to the soil (10.15 mg CH₄ kg⁻¹ soil). These results give an indication that soil properties influenced the production rate of CH₄ in an anaerobic soil condition.

In general the results show that addition of glucose to the soil increases CH₄ production. In practice, rice straw, which is a high carbon source, could increase CH₄ production as has been shown by Schultz and Seiler (1989). They mentioned that introducing rice straw in a reduced condition could decrease the redox potential status of the soil, and hence enhance CH₄ emission. Denier van der Gon et al. (1992) conducted a study at International Rice Research Institute on CH₄ emission and production from three different paddy soils of the Philippines, e.g., Pila, Luisiana and Maahas soils. The soils were treated with 1% rice straw over the weight of the soils. The soils were selected based on their different pH and some other chemical characteristics that are prone to CH₄ production. Maahas is a near neutral clay soil, Luisiana is an acidic clay soil with high iron content, and Pila is a calcareous sandy loam containing partly fragmented, mollusk shells. Results of their study showed that the CH₄ production rate in decreasing order is Pila soil > Luisiana soil > Maahas soil. The CH₄ production rate of Maahas soil was much lower than that in Pila and Luisiana, which was unexpected since Maahas soil was categorized as moderate in terms of soil characteristics for CH₄ production (active Fe, pH and organic C) (Table 3). Denier van der Gon et al. (1992) suggested that total organic carbon of soils did not directly correlate with CH₄ production. Therefore, other characteristics must be considered such as the chemical properties of the soils, which can influence the redox potential and pH status. In terms of soil organic carbon, determination of the soil organic fractions could possibly achieve better correlation with CH₄ production, i.e., reducible and non-reducible organic carbon.

Methane production from the brown-grayish Grumosol increased eight fold after the addition of glucose to the soil. The other soils produced higher CH₄ of twelve to thirty fold. One possible reason is that the redox potential of the brown-grayish Grumosol soil was below the optimal condition for methanogenesis. This issue needs further study because one of the most influential redox potential buffers in this soil, i.e., the Fe₂O₃ (citrate-dithionite) concentration was also low compared to the other soils. Data in Table 1 show that the Fe₂O₃ concentration was 1.46%, which is categorized as the second lowest Fe concentration compared with the other soils. The lowest values occur in gray Hydromorph Association, i.e., 0.31%.

The addition of glucose as a source of reducible C to the soil to elucidate the controlling factors of soil characteristic on CH₄ production potential did not entirely give the expected result. The glucose concentration applied to the soils was probably too high to represent reducible carbon occurring in natural conditions (1% of the total weight of soil used for incubation), and this possibly affected the micro-environment of the flooded soils such as pH.

Application of glucose to flooded soil changed the pH of the soil. Soils with low capacity to buffer pH drop could undergo extreme change in pH to low
values, and as such, are not suitable for methano-
genetic bacteria. The gray Hydromorph Association exhibits this characteristic. As has been discussed previously, the extreme drop in pH value was associated with reduced CH₄ production. Although other soils reacted similarly, the pH drop was not as extreme as that shown by the gray Hydromorph Association (Fig. 3), and conditions were still tolerable for methanogenic bacteria (pH 5.0-6.0).

**Determination of the Controlling Factors of CH₄ Production**

Soil characteristics, such as pH, sand, silt, clay, Mg, Cu, C/N, P, O₅, Fe₂O₅, N, SO₄, C-organic, MnO₂ were used in the stepwise multiple regression. Those parameters were involved in the reduction-oxidation processes and pH changes in soils. Using the stepwise multiple regression, five soil characteristics were found to greatly affect the CH₄ production, i.e., pH, Fe₂O₃, MnO₂, SO₄, and silt. The equation for the stepwise multiple regression is:

\[
\text{CH₄ production} = 7.88 + 4.57 \text{pH (H₂O)} - 0.03 \text{silt (‰)} - 0.015 \text{Fe₂O₃-total (‰)} + 0.088 \text{MnO₂-total (‰)} + 0.078 \text{SO₄₂⁻ available (ppm)}
\]

Soil pH affects the environmental conditions of methanogenic bacteria to produce CH₄. The optimum pH of paddy soils required by methanogenic bacteria is around 6.0-6.6. The same result was obtained by Wang et al. (1993b). The other elements, e.g., Fe₂O₃, MnO₂, and SO₄ contents in the soil affected the redox condition of soil.

Silt content of the soil highly affected the CH₄ production. Data from Table 2 show that most of the soils contained high amounts of silt, ranging from 30 to 71%. The lowest silt content occurs in red Latosol while the highest was found in gray-yellowish Alluvial. The sand distribution of the soils varied between 2 and 52%, while the clay ranged from 14 to 67%. The high content of clay occurred in dark-brown Alluvial soil while the lowest occurred in brown Regosol.

Research reported by Neue and Roger (1993) and Neue and Roger (1994) did not find the same results as obtained in Pati. They determined that reduced sandy soils with high organic carbon produced more CH₄ than clay soils with similar carbon contents. However, results from their experiment show that the active particle size distribution, i.e., clay, did not affect the production of CH₄, similar to the results obtained in Pati. The negative impact of clayey texture on CH₄ production may be caused by the formation of organo-mineral complexes. Sandy soils showed low entrapped CH₄ (Wang et al., 1993b) because the pore size distribution enhances ebullition and diffusion (Neue and Roger, 1993). Methane fluxes in clayey soils may also be lower because entrapped CH₄ may be oxidized before it can escape to the atmosphere. Methane production is limited in sandy soils if water percolation and the resultant redox potential are high. Disturbances of anaerobic conditions by cultural practices, e.g., puddling, transplanting, fertilization, and weeding could release soil-entrapped CH₄ to the atmosphere. Denier van der Gon et al. (1992) estimated that these soil disturbances contributed to about 10% to the total CH₄ emission.

Oxidized forms of components in the soil, such as Fe³⁺, Mn⁴⁺, and SO₄²⁻, will not be directly used as electron acceptors in biological reductions before all O₂ is released or used. After submergence, O₂ will dissolve in the flooded water and will be consumed quickly by microbes in the soil. The need for electron acceptors by facultative anaerobic and true anaerobic organisms results in the reduction of several oxidized components. Reduction of NO₃⁻ to NO₂⁻ and N₂O to N₂, Mn⁴⁺ to Mn³⁺, Fe³⁺ to Fe²⁺, SO₄²⁻ to S²⁻ and CO₂ to CH₄ will occur sequentially in flooded soil (because of thermodynamic principles) as long as available C sources exist and all entrapped O₂ is released (Patrick and Delaune, 1977). A corresponding decrease in soil Eh indicates the depletion of subsequent oxidants. For examples, nitrate is reduced to N₂O and N₂ in an Eh ranging between +250 to +350 mV. Manganic forms are reduced in slightly lower Eh range. Ferric iron reduction occurs in the range of +120 to +180 mV (Connel and Patric, 1969; Jakobsen et al., 1981).

Other compounds considered as micronutrients, i.e., Cu, Zn, and Mg, are probably involved in the metabolic activity of methanogenic bacteria. Their concentration in soil could enhance CH₄ production. The only reference available on the effect of micronutrients on CH₄ production was by Banik et al. (1995), which indicates that Zn is sensitive to methanogens at the concentration of 1-10 mg ml⁻¹. Cobalt is a constituent of cyanocobalamin, which is used for CH₄ production. Nickel is a constituent of urease, co-enzyme F₄₃⁰-, F₄₂⁰-reducing hydrogenase, and methyl reductase. Molybdenum, a constituent of nitrogenase and NO₃⁻ reductase, also stimulates CH₄ production in pure cultures of methanogens and in an anaerobic digester. In a supra-optimal concentrations, these elements could possibly decrease CH₄ emission, which is presumably due to saturation of the relevant enzyme surfaces, competition for
electrons between methanogens and $\text{SO}_4^{2-}$ and $\text{NO}_3^-$ reducers, and the development of toxicity (Banik et al., 1995).

**CONCLUSIONS**

Addition of 1% glucose to soil samples led to an increase in $\text{CH}_4$ production by more than twelve fold. The $\text{CH}_4$ production potential ranged between 3.21 and 112.30 mg $\text{CH}_4$ kg$^{-1}$ soil. The lowest $\text{CH}_4$ production potential occurred in brown-grayish Grumosol while the highest occurred in dark-gray Grumosol. Methane production potential of the soils without glucose addition ranged between 0.21 and 7.75 mg $\text{CH}_4$ kg$^{-1}$ soil. The lowest $\text{CH}_4$ production potential occurred in dark-gray Grumosol while the highest $\text{CH}_4$ production potential occurred in gray-yellowish Alluvial. Gray Hydromorph Association does not fit in this range because of its very high $\text{CH}_4$ production potential ($37.66 \text{ mg CH}_4 \text{ kg}^{-1} \text{ soil}$) compared with the other soils.

Chemical and physical properties of the soils have a great influence on $\text{CH}_4$ production. Stepwise multiple regression analyses of $\text{CH}_4$ production potential and soil characteristics show that soil pH and the contents of $\text{Fe}_2\text{O}_3$, $\text{MnO}_2$, $\text{SO}_4$, and silt in soil strongly influenced $\text{CH}_4$ production.

**ACKNOWLEDGEMENT**

The authors give special thanks to Mr. Jumari, Suryanto, Suyoto, Mr. Sudarmin, Mr. Yarpani, Ms. Titi Sopiawati and the other staff of the Jakenan Agricultural Environment Preservation Research Station, Pati, Central Java, who helped us conducting this study.

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