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RESEARCH ARTICLE

Effect of soil tillage and nitrogen fertilizer management on methane emissions from irrigated rice fields in Central Java, Indonesia

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ABSTRACT

Rice (*Oryza sativa* L.) production in the future aims to increase productivity every year with high input technology, including irrigated rice. However, the practices of irrigated rice fields have a high methane (CH_4) production potential. Soil tillage could affect CH_4 emission conditions. Puddling and flooding through soil tillage create reduction conditions that promote CH_4 production by methanogenic bacteria. The objective was to determine the effect of soil tillage and N fertilizer management on CH_4 emissions from rice fields with heavy-textured soil. The field experiment was arranged in a split-plot design in which soil tillage was the main plot and consisted of maximum tillage and no-tillage. Nitrogen fertilizer management was the split plot and consisted of a control without N, prilled urea broadcasting, prilled urea deep placement, ammonium sulfate (AS) broadcasting, AS deep placement, and tablet urea deep placement. No-tillage could reduce CH_4 emissions by 15.58% compared with maximum tillage. However, grain yield for no-tillage was lower than for maximum tillage with 2.73 and 3.68 t ha^{-1}, respectively. The AS and tablet urea deep placement emitted lower CH_4 and grain yield was higher than with other N management practices. The CH_4 emissions for AS and tablet urea deep placement was 96 and 97 kg CH_4 ha^{-1} $season^{-1}$ and grain yield was 3.79 and 4.25 t ha^{-1}, respectively. The application of fertilizers incorporated into the soil increased rice productivity and mitigated CH_4 emissions from rice fields.

Key words: Maximum tillage, methane emissions, nitrogen fertilizer, no-tillage, *Oryza sativa*, rice fields.

INTRODUCTION

Rice (*Oryza sativa* L.) is the most important food crop with an annual production of 81 million tons of dry unhusked rice (Connor et al., 2021). In 2020, rice fields in Indonesia accounted for 7.46 million ha, and more than half of this area was irrigated rice land (Mulyani et al., 2022). Mulyani et al. (2022) also reported that approximately 18.69% of the total irrigated rice fields were located in Central Java. Although rice is grown across the major islands of Indonesia, approximately 3.1 million ha are cultivated on Java Island (Agricultural Statistics, 2018; Connor et al., 2021). The mean productivity of irrigated rice fields is 5.65 t ha^{-1} (Mulyani et al., 2022). Rice production in the future aims to increase productivity every year to meet the demand for rice by the expanding human population.

Rice fields are a source of greenhouse gas (GHG) emissions, especially methane (CH_4) and nitrous oxide (N_2O) (Wang et al., 2017; Balaine et al., 2019; IPCC, 2019; Connolly et al., 2020). The GHG can gradually form a heat-emitting layer in the atmosphere that causes global warming. Methane is the second most abundant GHG; its global warming potential is approximately 25 times more potent than CO_2, and 7% to 17% of atmospheric CH_4 comes from flooded rice fields (Wang et al., 2017; Kim et al., 2018; Zhang et al., 2018a; Calvo Buendia et al., 2019; Gitarskiy, 2019). Human activities have increased the global concentration of GHG in the atmosphere. The CO_2 concentrations in the atmosphere increase 0.5% per year, while CH_4 concentrations increase 0.9% per year (Joos et al., 2013). Anthropogenic CH_4 emissions range from 540 to 568 Tg CH_4 per year, or 60% of total annual CH_4 emissions (Connolly et al., 2020). Global CH_4 emissions from rice fields expected for 2020 ranged from 29 to 61 t yr^{-1}, thus increasing CH_4 fluxes by up to 50% (Lai et al., 2021). This could undermine the benefits of the wetland system, which is the mainstay for the livelihood of most Asians, especially Indonesians.

Irrigated rice fields have a high potential for producing CH_4 (Balaine et al., 2019). Rice cultivation in water-saturated soils provides favorable conditions for methanogens in the rhizospheres, which anaerobically decompose the organic substrate to produce CH_4 (Balaine et al., 2019). The total CH_4 emissions from paddy fields mainly depend on a number of microbial-mediated processes in soils, such as CH_4 production and oxidation, and on numerous gas transport pathways, such as plant-mediated transport (through the aerenchyma), molecular diffusion, and ebullition (Bhullar et al., 2013). Methane is produced in anaerobic zones by methanogens, and 60% to 90% is subsequently oxidized by methanotrophs in the aerobic zones of the rhizosphere and converted into CO_2 (Wang et al., 2017). The extent of CH_4 production in the soil is influenced by several factors; these involve soil moisture conditions, C substrate, rice varieties and their characteristics (biomass and root exudation), soil properties such soil temperature, pH, and redox potential (Eh), and cultivation practices such as the use of both organic and inorganic fertilizers (Bhullar et al., 2013; Wang et al., 2017).

Intensive rice cultivation aimed at increasing productivity cannot be separated from the use of high input technology such as inorganic N fertilizers. The presence of nutrients in the rhizosphere of rice plants can stimulate microbial activity, including methanogens and methanotrophs. Nitrogen is one of the essential nutrients. Excessive N fertilizer application is inefficient and can pollute the environment. Soil N availability is an important controller and affects the emission rate, the CH_4 sink (Oertel et al., 2016). Nitrogen fertilization could reduce CH_4 sinks or increase CH_4 emissions because ammonium ions can inhibit methanotrophic bacteria from storing CH_4 (Zhang et al., 2020). However, the inhibition mechanism of ammonium loss is still unclear. Methanotrophic bacteria can oxidize ammonium, although ammonium oxidation is mostly carried out by ammonium oxidizing bacteria (Zhang et al., 2020). The ability of methanotrophs to oxidize ammonium and nitrifying bacteria in oxidizing CH_4 has raised questions about which organisms play a role in CH_4 and ammonium oxidation (Shiau et al., 2020). Therefore, the interaction between CH_4 oxidizing organisms and ammonium in the soil is very complex and involves substrate competition such as methane monooxygenase and ammonia monooxygenase (Serrano-Silva et al., 2014).

The development of agricultural technologies to increase crop productivity and mitigate GHG emissions is crucial for sustainable and productive rice-based systems (Zhang et al., 2013). Soil tillage is another agricultural practice that affects CH_4 emissions. The concept of soil tillage in the conservation system aims to reduce soil disturbance and improve soil aggregation, water infiltration, and nutrient availability (Ghimire et al., 2017). Soil cultivation in lowland rice cultivation creates suitable conditions for plant growth; therefore, not only can plant roots absorb soil nutrients freely, but also create reduction conditions that promote the development of methanogenic bacteria for CH_4 production (Krauss et al., 2017). No-tillage can also improve nutrient cycling, conserve water in the soil by increasing infiltration, reducing evaporation with a sufficient crop residue cover, and promote GHG mitigation (Ogle et al., 2019). In lowland rice cultivation, the appropriate low-emission technology is required to provide an optimal grain yield. Therefore, this study aimed to determine the effect of soil tillage and N fertilizer management on CH_4 emissions from irrigated rice fields.

MATERIALS AND METHODS

Experimental site

The study was conducted in paddy fields found in Wedarijaksa, Pati District, Central Java Province, Indonesia during the 2019 dry season. The experimental site was located at 6°70′15″ S 111°09′86″ E; the soil had a heavy texture containing sand, silt, and clay fractions up to 2%, 47%, and 51%, respectively. The soil was a Vertisol with acidic reaction, low C-organic and total N, low organic matter, high 25% P-extracted HCl, high available P-extracted Olsen, and very high 25% K-extracted HCl (Table 1). Exchangeable K and Na were low, while exchangeable Mg and Ca were from high to very high. The cation exchange capacity and base saturation were very high, while Al saturation was very low.

Table 1. Initial soil properties at the experimental site.

Variable	Value	Criteria (Eviati and Sulaeman, 2009)
pH (H_2O)	5.60	Slightly acid
pH (KCl)	4.60	Acid
Organic C, %	1.29	Low
Total N, %	0.17	Low
C:N ratio	8.00	Low
HCl 25% P_2O_5, mg kg^{-1}	185.00	Very high
K_2O, mg kg^{-1}	121.00	Very high
P_2O_5, mg kg^{-1} Olsen	58.00	High
K_2O, mg kg^{-1} Morgan	606.00	-
Exchangeable Ca, cmol kg^{-1}	25.71	Very high
Exchangeable Mg, cmol kg^{-1}	7.69	High
Exchangeable K, cmol kg^{-1}	1.28	Low
Exchangeable Na, cmol kg^{-1}	0.99	Low
Cation exchange capacity, cmol kg^{-1}	41.69	Very high
Base saturation, %	86.00	Very high
Exchangeable Al, cmol kg^{-1}	0.00	
Exchangeable H, cmol kg^{-1}	0.02	

Experimental design

The field experiment had a split-plot design and three replicates. The main plot was soil tillage that consisted of maximum tillage (T_1) and no-tillage (T_2), while N fertilizer management as a split plot consisted of a control without N fertilizer (N_1), prilled urea broadcasting (N_2), prilled urea deep placement (N_3), ammonium sulfate (AS) broadcasting (N_4), AS deep placement (N_5), and tablet urea deep placement (N_6). Maximum tillage was achieved by plowing twice followed by harrowing. In the no-tillage system, post-germination herbicide was applied 10 d before planting. The size of the experimental units (plots) was 4 m × 5 m.

Cultural practices

'Ciherang' rice (*Oryza sativa* L.) seeds were directly sown with a 20 × 20 cm spacing and 2 to 3 seeds per hole. The P and K fertilizers were applied in all plots at a rate of 45 kg P_2O_5 and 90 kg K_2O ha^{-1}, respectively. The N fertilizer rate was 112.5 kg N ha^{-1}. The N fertilizers with deep placement were applied 100% 30 d after germination (DAG), while N broadcasting was applied twice, 50% at 30 DAG and 50% at 50 DAG. The P fertilizer was applied at the same time as the first N fertilizer. The K fertilizer was applied twice, 50% at 30 DAG and 50% at 50 DAG. Plant maintenance was intensive through weeding and pest control in the field. Harvesting occurred after the rice plants entered the final maturity stage.

Observed variables and data analysis

The observed variables included CH_4 flux, soil pH, and redox potential (Eh), soil chemical properties before and after the experiment, and agronomic parameters (plant height, tiller number, fresh biomass weight, grain yield, and yield components). Plant height and tiller number were measured in 12 samples of randomly selected hills. Grain yield was measured from a 2 m × 3 m harvested area.

Gas samples were taken using the closed chamber method with 40 cm × 40 cm × 60 cm or 40 cm × 40 cm × 110 cm plexiglass boxes, which were adjusted to plant height. These samples were collected every 10 d at 06:00 h using a 5 mL volume syringe at 5 min intervals (5, 10, 15, and 20 min) after placing the box. Gas samples were analyzed in the laboratory by gas chromatography equipped with a flame ionization detector to determine the CH_4 concentration. The CH_4 emissions were computed by the equation used by Lantin et al. (1995):

$$E = \frac{\partial c}{\partial t} \; x \; \frac{Vc}{Ac} \; x \; \frac{mW}{mV} \; x \; \frac{To}{(To+T)}$$

where E is the CH_4 emission (mg m^{-2} d^{-1}), $\partial c/\partial t$ is the change in the CH_4 concentration per unit time (mg kg^{-1} min^{-1}), Vc is the chamber volume (m^3), Ac is the chamber area (m^2), mW is the molecular weight of

CH_4 (g), mV is the molecular volume of CH_4 (22.41 L), To is the Calvin temperature (273 °K), and T is the average temperature in the chamber during the air sampling time (°C).

Data were statistically analyzed with ANOVA software from SPSS Statistics 22 (IBM, Armonk, New York, USA). When the ANOVA was significant, a continuous test was performed with the least significant difference (LSD) at a 5% level to determine the significant difference between treatments.

RESULTS AND DISCUSSION

Soil chemical properties

Table 2 shows the effect of tillage and N fertilization treatments after the rice harvest on soil chemical properties such as pH, S, Fe, Mn, and C:N ratio. The treatment showed no difference in the mean soil pH value, which tended to be neutral (pH 6 to 8) and was higher than before the experiment (acid reaction). In no-tillage plots, soil pH was less than 7. Soil tillage affects the flooding conditions of rice fields. Maximum tillage experiences longer flooding conditions, while no-tillage dries faster. The pH in most soils shifts toward neutral after flooding. This shows that the pH of flooded soil is maintained at approximately the neutral point by the materials produced because of reduction reactions (Wei et al., 2020). Most CH_4-producing bacteria live at an approximately neutral pH (Enzmann et al., 2018). Soil reactions and microorganisms, including methanogenic bacteria, can function by obtaining energy through nitrate, Fe, Mn, sulfate, and organic matter reduction. The soil analysis showed that the oxidized S and Mn ions were 0.02% to 0.05% and 0.17% to 0.29%, respectively, and mean Fe was 3.17% to 3.88%. As the amount in the soil increases, it takes longer to form CH_4 in the soil because the electrons involved in CH_4 formation are preceded by the use of Mn, Fe, and S until they are all oxidized (Sigren et al., 1997; Yamamoto and Morii, 2020; Yorshansky et al., 2022). The level of organic matter decomposition is indicated by the C:N ratio of the soil. As the C:N ratio decreases, the decomposition of organic materials in the soil increases.

Table 2. Some soil chemical properties after harvesting the rice crops. Data are the mean of three replicates. AS: Ammonium sulfate.

	Treatments	pH	S	Fe	Mn	C	N
Tillage system	N Fertilization		%				
Maximum tillage	Without N	6.41	0.02	3.25	0.23	0.89	0.13
	Prilled urea broadcasting	7.07	0.04	3.59	0.29	0.78	0.13
	Prilled urea deep placement	7.01	0.04	3.47	0.21	1.03	0.13
	AS broadcasting	6.07	0.02	3.41	0.24	0.83	0.12
	AS deep placement	6.98	0.03	3.88	0.28	0.84	0.12
	Tablet urea deep placement	7.07	0.03	3.17	0.23	0.80	0.12
No-tillage	Without N	6.30	0.05	3.56	0.21	1.25	0.18
	Prilled urea broadcasting	6.50	0.03	3.76	0.22	0.96	0.15
	Prilled urea deep placement	6.50	0.03	3.29	0.17	1.19	0.16
	AS broadcasting	5.80	0.04	3.45	0.20	1.14	0.16
	AS deep placement	5.70	0.03	3.40	0.21	0.84	0.14
	Tablet urea deep placement	6.80	0.04	3.64	0.22	1.12	0.15

Plant growth and grain yield

Plant height and tiller number in the maximum tillage system were higher than in the no-tillage system (Tables 3 and 4). Soil cultivation is the mechanical manipulation of the soil, which is needed to create a good soil condition for plant growth (Alam et al., 2020). Puddling is the most important tillage practice. It can reduce water loss through percolation, reduce leaching of plant nutrients, and create favorable water conditions for the growth of rice plants (Alam et al., 2020).

Table 3. Plant height from soil tillage system and N fertilizer management in rice fields in Pati District, Indonesia, for the 2019 dry season. Numbers in the same column each factor followed by the same letter did not differ significantly at 0.05 of LSD. DAG: Days after germination; AS: ammonium sulfate.

Treatments	Plant height (cm)				
	30 DAG	45 DAG	60 DAG	75 DAG	90 DAG
Soil tillage system					
Maximum tillage	49.7[a]	55.3[a]	61.1[a]	67.7[a]	69.0[a]
No-tillage	47.4[a]	52.7[a]	56.6[a]	63.4[a]	61.4[a]
N fertilizer management					
Without N	45.6[b]	52.3[ab]	55.0[b]	60.2[b]	56.8[b]
Prilled urea broadcasting	48.9[ab]	54.9[ab]	59.8[ab]	64.5[ab]	64.8[a]
Prilled urea deep placement	49.3[ab]	55.1[ab]	60.5[a]	64.3[ab]	69.7[a]
AS broadcasting	49.4[ab]	53.8[ab]	58.7[ab]	68.8[a]	64.7[a]
AS deep placement	53.1[a]	56.6[a]	60.4[ab]	67.4[a]	70.2[a]
Tablet urea deep placement	45.1[b]	51.3[b]	58.8[ab]	68.0[a]	65.1[a]

Table 4. Tiller number from soil tillage system and N fertilizer management in rice fields in Pati District, Indonesia, for the 2019 dry season. Numbers in the same column each factor followed by the same letter did not differ significantly at 0.05 of LSD. DAG: Days after germination; AS: ammonium sulfate.

Treatments	Tiller number per hill				
	30 DAG	44 DAG	60 DAG	75 DAG	90 DAG
Soil tillage system					
Maximum tillage	5.6[a]	8.9[a]	11.4[a]	9.2[a]	10.1[a]
No-tillage	4.7[a]	6.8[a]	8.5[a]	8.5[a]	8.1[a]
N fertilizer management					
Without N	4.3[b]	6.2[c]	7.5[b]	7.2[b]	7.7[b]
Prilled urea broadcasting	4.9[b]	7.4[bc]	10.4[a]	9.4[a]	9.8[a]
Prilled urea deep placement	6.2[a]	9.7[a]	10.9[a]	9.1[a]	9.1[ab]
AS broadcasting	5.0[b]	7.3[bc]	10.2[a]	8.6[ab]	9.2[ab]
AS deep placement	6.2[a]	8.9[ab]	10.1[a]	8.6[ab]	8.9[ab]
Tablet urea deep placement	4.4[b]	7.5[bc]	10.6[a]	10.3[a]	10.0[a]

Nitrogen fertilizer application significantly affected plant height and tiller number, but the interaction of the N application and soil tillage system did not significantly affect them (Tables 3 and 4). Plant height when using N fertilizer deep placement is generally higher than for broadcasting. Tiller number development was influenced by urea application due to the growth of new root tips stimulated by N. Therefore, applying fertilizer around the plant roots accelerates the process and enables plant roots to absorb more N. Appropriate fertilizer placement is very effective in minimizing N loss through volatilization. The volatilization rate is higher when the fertilizer is applied on the soil surface. Li et al. (2017) stated that the fertilizer deep placement decreased fertilizer loss through volatilization.

The tillage system used on the rice paddy Vertisol did not significantly affect yield, yield components, and N fertilization. However, N fertilizer management had a significant effect on grain yield and yield components (Table 5). The application of N deep placement produced significantly higher grain yield and yield components than broadcasting, especially for tablet urea and AS. The highest grain yield was obtained for urea tablet deep placement. Under reduction conditions, plants absorb urea as NH_4^+. The presence of NH_4^+ in the soil cannot be separated from the various processes of N transformation such as nitrification, volatilization, and fixation (Ishii et al., 2011; Zhang et al., 2018b). Volatilization of NH_3 is the most detrimental process because it reduces available N for plants, which also results in reduced benefits from the use of N fertilizers (Li et al., 2017). The volatilization process is much faster when the fertilizer is applied on the soil surface. When the fertilizer is placed deeper, fertilizer loss through volatilization tends to decrease. The deeper the fertilizer application, the wider the cation exchange complex has the opportunity to adsorb volatilized NH_4^+ (Ishii et al., 2011; Zhou et al., 2022).

Table 5. Grain yield and yield components from soil tillage system and N fertilizer management in rice fields in Pati District, Indonesia, for the 2019 dry season. Numbers in the same column each factor followed by the same letter did not differ significantly at 0.05 of LSD. AS: Ammonium sulfate.

Treatments	Grain yield	Dry straw weight	Panicle number per hill	Panicle length	Filled grain number per hill	Unfilled grain number per hill	1000 grain weight
	t ha^{-1}	t ha^{-1}	nr	cm	nr	nr	g
Soil tillage system							
Maximum tillage	3.68^{b}	6.24^{a}	10.11^{a}	19.78^{a}	544^{a}	152^{a}	26.04^{a}
No-tillage	2.73^{a}	4.81^{a}	9.62^{a}	18.51^{a}	447^{a}	106^{a}	24.93^{a}
N fertilizer management							
Without N	1.34^{c}	2.56^{c}	5.90^{c}	16.92^{c}	186^{c}	56^{c}	23.65^{c}
Prilled urea broadcasting	3.28^{b}	5.44^{b}	9.60^{b}	18.90^{b}	433b	109^{bc}	25.51^{b}
Prilled urea deep placement	3.39^{b}	5.95^{b}	10.53^{ab}	19.53^{ab}	594^{a}	137^{ab}	26.39^{a}
AS broadcasting	3.19^{b}	5.35^{b}	9.70^{b}	19.73^{ab}	466^{b}	133^{ab}	25.81^{ab}
AS deep placement	3.79^{ab}	6.61^{ab}	11.07^{a}	20.30^{a}	618^{a}	175^{a}	25.79^{ab}
Tablet urea deep placement	4.25^{a}	7.23^{a}	12.40^{a}	19.50^{ab}	677^{a}	168^{ab}	25.77^{ab}

Methane flux

Figure 1 shows the pattern of CH_4 flux during the growing season of the rice crop. For both the maximum tillage and no-tillage treatments, CH_4 flux was 10 mg CH_4 m^{-2} d^{-1} or more at the initial rice growth stage and it increased in the active tillering stage to the maximum tillering stage. The CH_4 rate peaked at the maximum tillering stage and then declined at the maturity stage (Oda and Chiem, 2019). The pattern of CH_4 flux decreased from 60 DAG until the ripening stage or before harvesting the rice plants. The daily CH_4 flux from paddy fields in a Vertisol was lower than results reported by Setyanto and Bakar (2005), who reported the mean CH_4 flux from irrigated rice fields in an Inceptisol that ranged from 71 to 217 mg CH_4 m^{-2} d^{-1}. The low daily CH_4 flux in Vertisols is presumed to have much less CH_4 trapped in the macropores than Inceptisols; therefore, it is also released to the atmosphere at a lower rate. Water regimes and groundwater levels influence CH_4 patterns. Low Eh conditions from -100 to -150 mV are favorable for the activity of CH_4-producing bacteria in the soil (Setyanto and Bakar, 2005). Figures 2a and 2b show that the soil was under waterlogged conditions during the growth of the rice plant, which resulted in a low Eh value.

Excess water or soil flooding affects the physical and chemical properties of wetland soil. The change in the physical and chemical properties is caused by a biological redox process due to oxygen depletion in the soil. The change in Eh is an important process in CH_4 formation. Increasing the soil Eh value reduced CH_4 emissions. The soil Eh observations during plant growth resulted in a minimum soil Eh value of -247 mV and maximum of 0 mV (Figure 2). The mean soil Eh value from maximum tillage was higher than for no-tillage, whereas the management of N fertilizers applied by broadcasting showed the highest Eh fluctuation. The low Eh value was influenced by the reduction soil conditions due to the flooding process of the maximum tillage system. Limited oxygen as a center for oxidants causes oxygen-deprived soil reactions to proceed in a reductive manner. Urea in the soil is directly hydrolyzed by the urease enzyme into CO_2 and NH_3 so that soil pH becomes alkaline, followed by decreased soil Eh (Lasisi and Akinremi, 2021; Zhao et al., 2022).

Figure 3 illustrates CH_4 gas emissions in the tillage system and N fertilizer management in a rice field. In the no-tillage plots, the CH_4 emission was lower than for maximum tillage. Soil tillage with repeated lubrication creates an impervious layer, which can inhibit the infiltration rate, and the soil becomes reductive with a negative Eh value. Decreasing the infiltration rate can promote the efficient use of irrigation water and simultaneously reduce nutrient losses due to leaching or percolation (Alam et al., 2020). This condition has great benefits for methanogenic bacteria in the production of CH_4. Methanogens are very active under anaerobic conditions and cause the process of organic matter decomposition (Rahim et al., 2015; Lai et al., 2021).

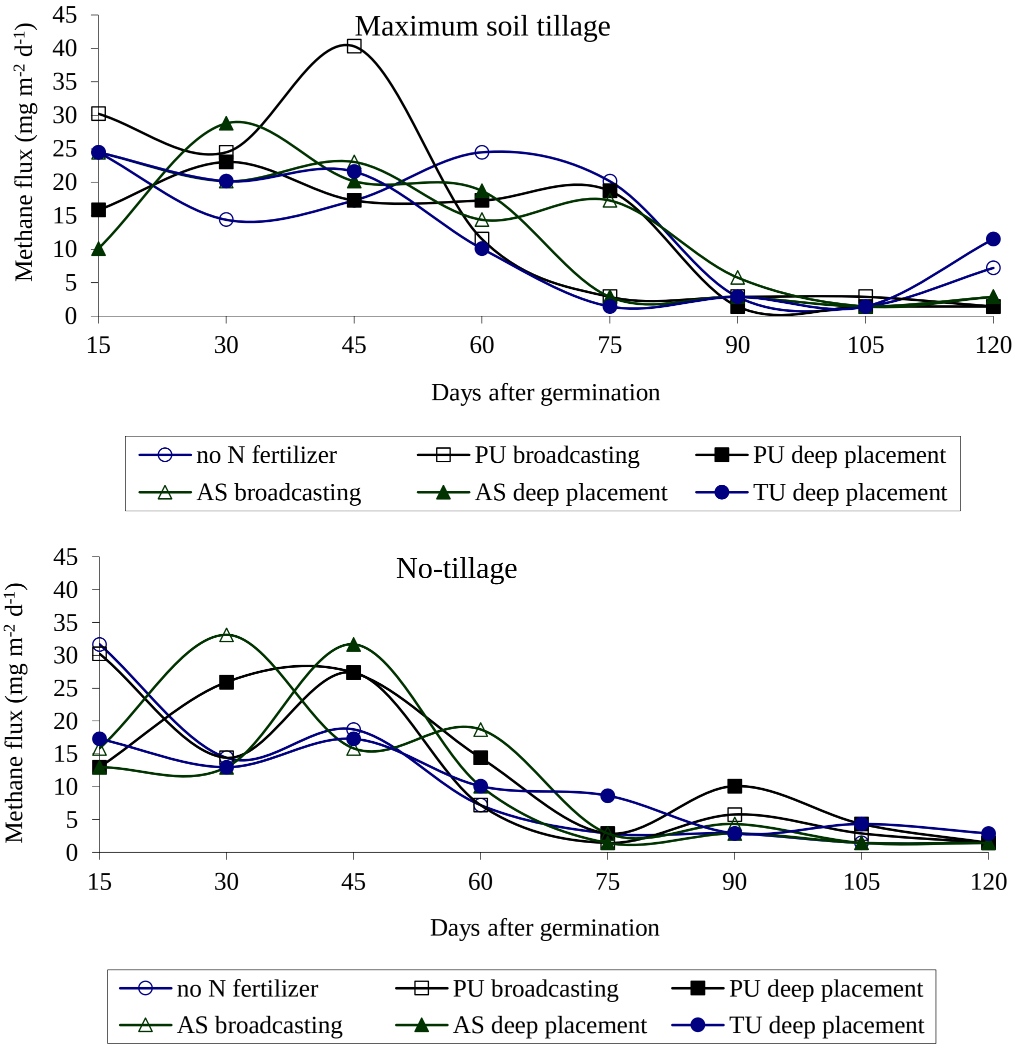
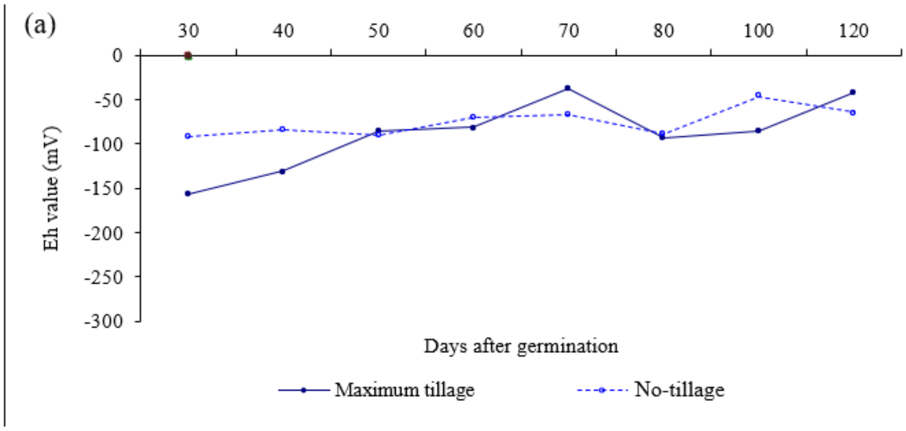


Figure 1. Pattern of methane flux from soil tillage system and N fertilizer management in rice fields in Pati district, Indonesia, for the 2019 dry season. PU: Prilled urea; AS: ammonium sulfate; TU: tablet urea.



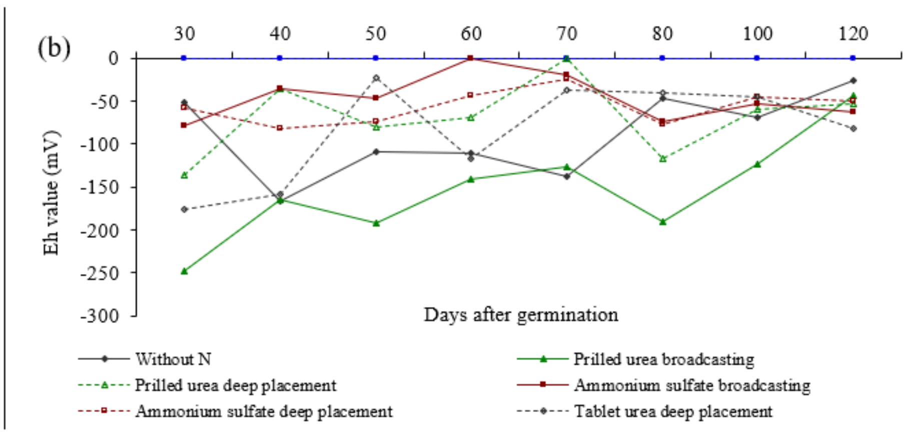


Figure 2. Soil redox potential (Eh) from tillage systems (a) and N fertilizer management (b) in rice fields in Pati district, Indonesia, for the 2019 dry season.

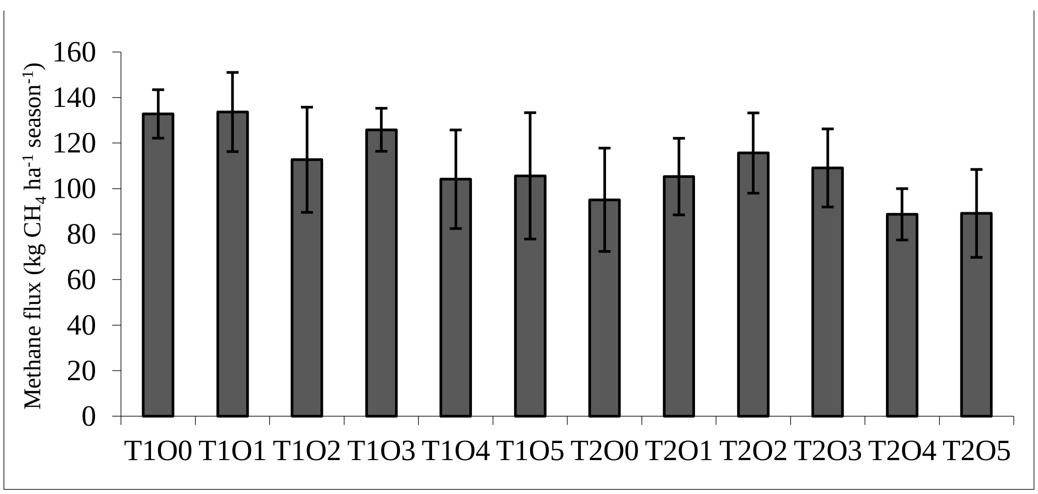


Figure 3. Methane emission from soil tillage system and N fertilizer management in rice field in Pati district, Indonesia, 2019 dry season. T1: Maximum tillage; T2: no-tillage; O0: without N; O1: prilled urea broadcasting; O2: prilled urea deep placement; O3: ammonium sulfate broadcasting; O4: ammonium sulfate deep placement; O5: tablet urea deep placement.

Nitrogen fertilizers are needed for the growth of rice plants; they influence root development in the rhizosphere where CH_4-forming bacteria are located. Nitrogen fertilizers applied deeper in the soil in the reduction soil layer emit lower levels of N than broadcasting. The lowest emission, 96.40 kg ha^{-1}, was reached with the AS deep placement application. The inhibition of CH_4 emissions appears to be due to the enhanced diffusion process of oxygen to the soil reduction layer; CH_4-reducing bacteria oxidize the gas and CH_4 that is formed is partially oxidized before being released to the atmosphere. The type of N fertilizer affects the amount of CH_4 flux. The CH_4 emissions from tablet urea were lower than AS, while AS was lower than prilled urea. The AS fertilizer at a 500 kg ha^{-1} rate reduced CH_4 emissions by 31.4 g m^{-2} h^{-1} and was 25% lower than the 250 kg ha^{-1} urea rate (Nugroho et al., 1994). Minamikawa et al. (2005) and Kibangou et al. (2022) stated that N fertilizers containing sulfate (AS) could produce methanogenic bacteria to compete with sulfate-reducing bacteria for hydrogen, thus inhibiting CH_4 formation. Meanwhile, without N fertilizer, CH_4 emissions were quite high (113.48 kg ha^{-1} $season^{-1}$). This could be related to the results of the previous decomposition process of plant residues and rice roots, which used methanogens as a source of energy and C; therefore, the activity of methanogenic bacteria was greater in CH_4 gas production.

CONCLUSIONS

Nitrogen fertilizer management in paddy fields has a significant effect on methane (CH_4) emissions, although the interaction of N fertilizer and tillage system did not significantly affect CH_4 emissions. Maximum tillage produced higher CH_4 emissions than no-tillage. The means for CH_4 emissions from rice fields with the maximum tillage and no-tillage systems were 119 and 105 kg CH_4 ha^{-1} $season^{-1}$, respectively. Incorporating N fertilizers to the soil emits CH_4 at a lower rate than broadcasting N fertilizers. Applying ammonium sulfate (AS) and tablet urea to the soil emits CH_4 at a lower rate than prilled urea with values of 96, 97, and 114 kg CH_4 ha^{-1} $season^{-1}$, respectively. The interaction of soil tillage systems and N fertilizer management did not significantly affect the yield of lowland rice. Grain yield with maximum tillage was significantly higher than for no-tillage. Relatively high grain yields were achieved with AS and urea tablet deep placement.

Author contribution

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