Effects of rice cultivar on the net greenhouse gas emission under continuous flooding and alternate wetting and drying irrigations in paddy field

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Abstract. Rice production has been challenged by increasing food demand and water scarcity. Alternate wetting and drying (AWD) irrigation is a water-saving irrigation technique for paddy fields. The aim of this research was to determine the effects of rice cultivars on the net greenhouse gas emission under continuous flooding (CF) and AWD irrigations in paddy field. This experiment used randomized complete block design with combination of the water management systems and rice cultivars. There were two water management systems, namely (1) CF and (2) AWD irrigations and three rice cultivars, namely (1) Ciherang, (2) Inpari 32, and (3) Mekongga. The results showed that the AWD irrigation decreased global warming potential by 51%, 40% and 19% when combined Ciherang, Inpari 32, and Mekongga, respectively, compared to CF. The combination of AWD irrigation and Inpari 32 rice cultivar resulted in the highest net GHG balance among all treatments approximately 7.9 t ha⁻¹ and also showed the highest profit around IDR 18.3 million ha⁻¹. This study clearly suggested the possibility of reducing GHG emission from the paddy field through appropriate selection of water management and rice cultivars to achieve a technically and economically feasible as a mitigation option.

1. Introduction

Global warming and food security are both important global issues. Food demand is projected to increase 70% by the year 2050 due to a rapidly growing population. Greenhouse gas (GHG) emissions from agriculture tend to increase over 70% of the total allowable budget of emissions from all human induced activities [1]. Globally, GHGs emission in the agricultural sector increased by 35%, from 4.2 Gt CO₂-eq yr⁻¹ to 5.7 Gt CO₂-eq yr⁻¹ during 1970 to 2010 [2]. Agricultural methane (CH₄) and nitrous oxide (N₂O) are two GHGs which considered to contribute significantly to climate change [3].

Irrigated agriculture is one of the major consumers of freshwater accounting for 70% of water withdrawal globally [4]. Rice fields under continuous flooding are the potential source of CH₄ production. Several strategies for mitigating CH₄ emission from rice cultivation are water management, particularly promoting intermittent drainage and alternate wetting and drying (AWD) [5]; adopting direct-seeding of rice (DSR) [6] and system of rice intensification (SRI) [7]; improving organic management by composting; using rice cultivars with few unproductive tillers, high root oxidative activity and high harvest index [8]; and application of fermented manure like biogas slurry [9].

Methane is a gas emitted from irrigated rice fields affected by the processes of production, oxidation and transportation. The emission of CH₄ to the atmosphere consists of three pathways: molecular diffusion, ebullition and plant-mediated transport. Rice plant have three roles related CH₄ emission [8]:
i) providing substrate through root exudates and/or decay root cells; ii) as a chimney (aerenchyma) in leaf blades and sheaths, culms, and roots of rice plants, which have a large capacity for CH\textsubscript{4} transport to the atmosphere [10]; and iii) supplying oxygen to rhizosphere in CH\textsubscript{4} oxidizing site [11].

The CH\textsubscript{4} emissions from paddy fields can vary depend on various factors such as rice cultivars, methanogen and methanotroph composition in the root zone, growth stages of the rice plants and environmental conditions likely soil under cultivation and other agricultural practices such as water management, manure and fertilizer application. Even though the methane emission in paddy fields is influenced by various factors; genotypic variation contributed more and substantial differences up to 56% among cultivars [12]. Among the climatic, environmental and field management factors influencing methane emissions from rice paddy, rice cultivar is one of the most influential factors [13]. Water management and selecting of rice cultivar that emits lower CH\textsubscript{4} and N\textsubscript{2}O emissions may therefore be a promising option to mitigate GHG emissions from paddies fields. Thus, the aim of this research was to determine the effects of rice cultivars on the net greenhouse gas emission under continuous flooding (CF) and AWD irrigations in paddy field.

2. Materials and methods

2.1. Experimental site and design

Field experiment was conducted at the experiment station of Indonesian Agricultural Environment Research Institute (IAERI), Pati, Central Java. Our field experiment was carried out during rainy season from November 2017 to February 2018. The soil of the paddy field was poorly nutrients and classified as Aeric Endoaquepts [14]. The average of air temperature and precipitation during rice growing season at this site were 32°C and 830 mm, respectively (figure 1).

![Figure 1](image_url)  
Figure 1. Temporal variations of air temperature and rainfall in the paddy field over the study period.

The experiment was designed using randomized complete block design with the combination of water management systems and rice cultivars. There were two water management systems:(1) continuous flooding irrigation, (2) alternate wetting and drying. The second factor was rice cultivars: (1) Ciherang, (2) Inpari 32, and (3) Mekongga. The each experimental pot was 5 m x 5 m in size and each treatment had three replications. In the continuous flooding condition, the plant was kept flooded at 5 cm above soil surface during the whole growing period; and in the alternate wetting and drying treatment, the rice was flooded at 5 cm when the water level reached 15 cm below soil surface during the whole growing period.
All treatments received the same fertilizer management. The field was ploughed to a depth of 20 cm and levelled 2 days before direct seeding. The farm yard manure (FYM) application with a dose of 3 t ha\(^{-1}\) was given during the soil preparation. Chemical fertilizers consisted of P (SP-36) 90 kg P\(_2\)O\(_5\) ha\(^{-1}\), N fertilizer (Urea) 120 kg N ha\(^{-1}\), and K fertilizer (KCl) 90 kg K\(_2\)O ha\(^{-1}\). The P fertilization was utilised during the soil tillage as a basalt fertilizer. The first fertilization was in the form of ½ N and ½ K fertilizers, the second N fertilization were given based on Leaf Color Chart (LCC). The observed parameters were fluxes CH\(_4\) and N\(_2\)O, water level, grain yield, carbon content of soil and plant.

2.2. Soil and plant sampling and analysis
Before planting and after harvesting, background soil samples (0-20 cm) were collected, air dried, ground and sieved (<2 mm) for the analyses of soil organic carbon content. Soil organic carbon content was determined for total carbon content by high-temperature combustion using a Total CN analyzer (Scalar, USA). The SOC storage was calculated as follows [15]:

\[
SOC = 100 \times h \times \rho \times C \quad (1)
\]

where \(h\) represents the soil depth (cm), \(\rho\) is soil bulk density (g cm\(^{-3}\)), and \(C\) is the content of SOC (g kg\(^{-1}\)). After harvesting, two hills were taken out for above and root biomass. Roots were separated from above biomass. Roots were washed with water and sun-dried. Dry above biomass and root were determined for total carbon content as follows:

\[
C_{\text{plant}} = B_1 \times C_1 + B_2 \times C_2 + B_3 \times C_3 + B_4 \times C_4 \quad (2)
\]

where \(C_{\text{plant}}\) represents a plant’s organic carbon (kg ha\(^{-1}\)), \(B_1\) is the above biomass of the rice plant (kg ha\(^{-1}\)), \(B_2\) is the biomass of the rice root, \(B_3\) is the biomass of the rice grain. Similarly, \(C_1\) is the organic carbon of above biomass (g kg\(^{-1}\)), \(C_2\) is the organic carbon of the rice root, \(C_3\) is the organic carbon of the rice grain. The crop yield (t ha\(^{-1}\)) was determined by harvesting 2 x 3 m\(^2\) harvest area, weighing them and then converting t ha\(^{-1}\).

2.3. Gas sampling and analysis
Methane (CH\(_4\)) and nitrous oxide N\(_2\)O fluxes of paddy field were measured by taking samples of CH\(_4\) and N\(_2\)O using closed chambers that non-permanently installed in the field. The sizes of chambers were 50 x 50 x 100 cm and 20 x 40 x 30 cm for CH\(_4\) and N\(_2\)O, respectively. One butyl rubber septum port was installed on the top of the chamber. Gas samples were taken by inserting a 10 ml syringe through a butyl rubber septum in the chamber lid and, after gently pumping the syringe several times, 20 ml gas sample were withdrawn and flush into a 10 ml glass storage vial. The gas sampling was done weekly. The CH\(_4\) gas samples were collected during 06:00 to 09:00 AM at 5, 10, 15, 20 and 25 min after the top chamber was covered and at 10, 20, 30, 40 and 50 min for N\(_2\)O gas samples. The samples were analyzed using Gas Chromatography equipped with flame ionization detector (FID) and electron capture detector (ECD). Flux of CH\(_4\) and N\(_2\)O were calculated using the following equation [16]:

\[
E = \frac{dc}{dT} \times \frac{Vch}{Ach} \times \frac{mW}{mV} \times \frac{273.2}{273.2+T} \quad (3)
\]

where \(E\) is flux of CH\(_4\)or N\(_2\)O (mg m\(^{-2}\)day\(^{-1}\)), \(dc/dT\) is delta concentration of CH\(_4\) or N\(_2\)O (ppm minute\(^{-1}\)), \(Vch\) is volume of chamber (m\(^3\)), \(Ach\) is area of box (m\(^2\)), \(mW\) is molecular weight of CH\(_4\) or N\(_2\)O (g), \(mV\) is molecular volume of CH\(_4\) or N\(_2\)O, and \(T\) is average temperature at sampling time (°C). The flux of CH\(_4\) and N\(_2\)O was then converted as global warming potential from soil (GWP\(_{\text{soil}}\)) into kg CO\(_2\)-e ha\(^{-1}\) season\(^{-1}\). The GWP\(_{\text{soil}}\) of CH\(_4\) is 34 and N\(_2\)O is 298 [17] and the calculation of GWP\(_{\text{soil}}\) used the equation:

\[
\text{GWP}_{\text{soil}} = (\text{cumulative CH}_4 \text{ emission} \times 34) + (\text{cumulative N}_2\text{O emission} \times 298) \quad (4)
\]
The results were also presented as GHG intensity (GHGI) and carbon efficiency. Carbon efficiency is ratio economic benefit per unit emission. The GHGI is the ratio of the total warming potential of CH$_4$ and N$_2$O to crop yield of each treatment [18].

2.4. Net greenhouse gas balance

The net greenhouse gas balance can be converted to its CO$_2$ equivalent (CO$_2$-eq) using the global warming potential [19]. It can be calculated as follows:

$$\text{NGHGB} = \text{GWP}_{\text{soil}} - \text{GWP}_{\text{SOC}} - \text{GWP}_{\text{plant}}$$

where NGHGB indicates the sink or source of GHG. GWP$_{\text{SOC}}$ represents the GWP caused by the SOC change in the soil. It can be calculated as follows:

$$\text{GWP}_{\text{SOC}} = \text{SOC}_A - \text{SOC}_B$$

SOC$_A$ (kg ha$^{-1}$) and SOC$_B$ represent the carbon storage after rice harvesting and before rice planting, respectively. GWP$_{\text{plant}}$ (kg ha$^{-1}$) represents the GWP caused by the carbon storage of plants. It can be calculated as follows:

$$\text{GWP}_{\text{plant}} = C_{\text{plant}} \text{ quantities of crops per ha}/1,000$$

2.5. Data and statistical analyses

Statistical analyses was done using SAS software (SAS Institute 1995). A one-way ANOVA was carried out to compare the treatment means. Least significant difference (LSD) was calculated at 0.05 probability for making treatment mean comparisons.

3. Result and discussion

3.1. Effect of water management and rice cultivar on the GHG Emission

The methane emissions varied during the growth period of the plant from all the treatment plots. In general, CH$_4$ flux was low during the early growth stages (tillering stage) of the rice plant, but then increased to a seasonal peak during the maximum tillering stage (figure 2A and 2B). The CH$_4$ fluxes increased with plant growth because of water availability derived from the rainfall as shown in Figure 1. The flooding periods and temperature helped to accelerate the increase of CH$_4$ flux. Drying of the field during later stages (before the flowering stage) could cause in a greater reduction in CH$_4$ emissions. The gradual increase of CH$_4$ emissions after flooding was consistent with anoxic condition in flooded soil. Maximum CH$_4$ were measured during the reproductive and ripening stages and this is probably due to higher availability of fatty acids and sugars released by plant root [20].

The CH$_4$ fluxes of AWD-Inpari 32 and AWD-Mekongga decreased drastically at 56 DAS and 70 DAS, may be caused by the effect of AWD cycles during the rice growing period. The drainage condition is an important management practice to supply rice roots with O$_2$ to prevent sulphide toxicity and also helps to reduce CH$_4$ emission [21]. There were differences of CH$_4$ emissions among rice cultivars during the growth stage because of rice morphology and changing of size and therefore also the way the rice plant emits CH$_4$ [22]. Moreover, carbon content in the soil is positively correlated with CH$_4$ emission in CF and AWD plots [23]. The seasonal CH$_4$ emissions in this study ranged from 141 to 293 kg ha$^{-1}$. The CH$_4$ emissions from paddy field during rainy season were lower than dry season that ranged from 193 to 367 kg ha$^{-1}$ [14]. In this location, the field was more inundation in the early until the middle of dry season (figure 1), so the organic materials from plant residues decomposed and became the main source of methanogenic substrates. The values of CH$_4$ emission in this study were higher than the default of baseline CH$_4$ emission factor by 1.3 kg CH$_4$ ha$^{-1}$ day$^{-1}$, in continuous flooding rice cultivation [24], because in tropical condition which highly rainfall and warmer temperature would stimulate CH$_4$ production. Overall, CH$_4$ flux from the AWD treatments with three rice cultivar were
significantly lower than those from CF by 52%, 41% and 19%, respectively (P<0.05) (figure 2A and 2B). In this experiment we were found also CH$_4$ emissions from rice field to be positively correlated with above (y = 0.001x + 4.103, R=0.023) (Figure 2A and 2B), tiller number (y = 0.009x + 8.573, R=0.387), but negatively correlated with rice harvest index (y = -0.0001x + 0.529, R=0.031).

Figure 2. Seasonal variations of CH$_4$ emissions from the CF plots (A) and AWD (B) plots, Pati, rainy season 2017-2018. The bar with each point indicates the range of the standard error (SE) of the mean. Downward arrows indicate the time of fertilization.

The N$_2$O emissions fluctuated within a negligible level over the course of the investigation period compared to the CH$_4$ emission rates. It seems that N$_2$O fluxes higher in the early growing because of water condition and then fluctuated after flooding (figure 3A and 3B). The timing of peak N$_2$O emissions varied widely among the plots. The highest N$_2$O flux detected at 70 DAS in the AWD-Ciherang plot (509 µg m$^{-2}$ day$^{-1}$). The overall mean N$_2$O emission from AWD combined three rice cultivars were not significantly higher than those from continuous flooding plots (P<0.05) (figure 4B). The similar finding also reported that no significant difference (p<0.05) in daily N$_2$O emission between AWD and continuous flooded plots [23]. In this experiment, the seasonal N$_2$O emissions from paddy field were relatively lower (<0.5 kg ha$^{-1}$) than the similar study which used Cisadane rice variety (>0.7 kg ha$^{-1}$) [25].

Global warming potentials (GWP$_{soil}$) were significantly influenced by the water management and rice cultivars (figure 4C). The GWP$_{soil}$ from the AWD combined three cultivars were found to be significantly lower (p <0.05) with CF. The highest of GWP$_{soil}$ was 10,018 kg CO$_2$-e ha$^{-1}$ from CF-Ciherang plot and the lowest was AWD-Ciherang. Compared with CF, GWP$_{soil}$ reduction from AWD were significantly different (P<0.01) and reduced GWP$_{soil}$ by 51%, 40% and 19% when combined Ciherang, Inpari 32 and Mekongga rice cultivars, respectively. Figure 4C also showed that CH$_4$ emission has greater contribution to GWP$_{soil}$ value in paddy fields than N$_2$O emission. The AWD treatment was most effective in reducing the adverse impact of rice cultivation on climate change, with significantly lower total GWP$_{soil}$ in three rice cultivars compared to the continuous flooding. Rice is grown in flooded systems, prevent oxygen from entering the pores. Rice is a crop which is grown majorly in irrigated flooded ecosystem and it is mainly issued for two interrelated components contributing to climate change, i.e. CH$_4$ emissions and inefficient water use.
Figure 3. Seasonal variations of $\text{N}_2\text{O}$ emissions from the CF plots (A) and AWD (B) plots, Pati, rainy season 2017-2018. The bar with each point indicates the range of the standard error (SE) of the mean. Downward arrows indicate the time of fertilization.

Figure 4. $\text{CH}_4$ emission (A), $\text{N}_2\text{O}$ emission (B) and GWP$_\text{soil}$ (C) under water management and rice cultivar treatments, Pati, rainy season 2017-2018. The bar with each point indicates the range of the standard error (SE) of the mean.

The average water depths of CF plots and AWD plots are shown in Figure 5. Average water depth of plots under CF condition were ranged from 3.7 cm to 5.0 cm. Water depth was almost similar in CF for all rice cultivar treatment. AWD plots were in drying condition only two times (10 days in total) during the whole rice growing. Under AWD condition, average water depths ranged from $-15.0$ cm to 5.0 cm. The negative value of water depth indicated that the depth of water below soil surface. AWD plots were irrigated when water goes below 15 cm from soil surface. We found that AWD irrigation combined Ciherang, Inpari 32, and Mekongga rice cultivars save 16%, 26% and 20% of water input, respectively, compared to CF without significant yield reductions (4.55 vs 4.61 t ha$^{-1}$ with the average of brown rice grain at 14% w.c). Data from some countries showed that there was a yield reduction or increasing by AWD, while other studies showed the AWD have no effect on yields if done properly [1]. AWD irrigation technique reduces water use by up to 30% without impacting yield. AWD has been
widely examined and is now being adopted in many Asian countries with large scale in the Philippines, Vietnam, and Bangladesh [26].

Figure 5. The average water depths under different water management and rice cultivars treatments, Pati, Rainy Season 2017-2018.

3.2. Economic analysis, carbon efficiency and net greenhouse gas balance (NGHGB)

Based on the economic calculation of rice production, the CF with all cultivars needed a higher cost production than AWD (Table 1). The AWD-Ciherang treatment gave the least of cost production, followed by AWD-Inpari 32 and AWD-Mekongga treatments. The difference of cost production among the treatments was resulted from irrigation cost. The higher profits were attributed to higher grain with a lower irrigation cost. The highest profit (IDR 18.3 million) was obtained from AWD-Inpari 32 treatment with BC ratio 1.90. The AWD-Inpari 32 treatments gave the lowest GHG intensity (GHGI) which has higher yield potential but lower GHG emission. The combination of AWD irrigation and Inpari 32 rice cultivar was found to be economically viable in view of higher profit and BC ratio owing to higher grain yield with marked carbon efficiency.

The GWP of soil organic carbon in this study ranged from 73 to 99 kg CO\(_2\)-e ha\(^{-1}\). AWD combined Ciherang rice gave the lowest GWP\(_{SOC}\) (73 kg CO\(_2\)-e ha\(^{-1}\)) because of lower below ground biomass then resulted in lower soil organic content after harvesting. The lowest of net GHG emission (NGHGB) in this study was from CF combined Ciherang treatment by 2,312 kg ha\(^{-1}\). The AWD irrigation combined Inpari 32 rice cultivar was the highest GHG intensity (GHGI) which has higher yield potential but lower GHG emission. The combination of AWD irrigation and Inpari 32 rice cultivar was found to be economically viable in view of higher profit and BC ratio owing to higher grain yield with marked carbon efficiency.

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The negative remark showed the “sink” of the GHGs (Table 2). The net GHG balance of the tropical paddy rice ecosystem were mainly sequestered rather than being emitted. The net GHG balance of AWD-Ciherang, AWD-Inpari 32, and AWD-Mekongga increased by 75%, 26%, and 33%, respectively, more than that of the CF-Ciherang, CF-Inpari 32, and CF-Mekongga treatments. This indicated that the effect of rice cultivars on greenhouse gas emission reduction under the AWD water management was better than that under the CF condition. By shifting water management from the current practice to intermittent flooding in all the irrigated rice area of the country, the national CH\(_4\) emission from irrigated rice fields could be reduced by 40%. However, under the intermittent flooding scenario, the \(N_2O\) fluxes could increase by 6% [27]. Our results emphasize that NGHGB is needed to support the government of national low carbon development. Varietal selection is important to find cultivars with high yielding and low methane emissions, and thus a lower GHGI potential. The ideal rice cultivars for reducing CH\(_4\) emissions should have a high harvest index, less ineffective tillers, and high root oxidizing power [28]. In summary, the combination of AWD irrigation and Inpari 32 rice cultivar treatment could not only reduce greenhouse gas emission from paddy soil, but also maintain land resources for better crop production sustainably.
Table 1. Economy analysis, GHGI and carbon efficiency under water management and rice cultivars treatments, Pati, rainy season 2017-2018.

| Treatment      | Yield (t ha\(^{-1}\)) | Revenue (IDR ha\(^{-1}\)) | Cost Prod (IDR ha\(^{-1}\)) | Profit (IDR ha\(^{-1}\)) | BC ratio | GHGI | Carbon Efficiency |
|----------------|------------------------|-----------------------------|-----------------------------|----------------------------|-----------|------|-------------------|
| CF-Ciherang    | 4.34                   | 24,478,392                  | 10,800,000                  | 13,678,392                 | 1.27      | 2.31 | 1,365             |
| CF-Inpari 32   | 5.11                   | 28,827,781                  | 10,800,000                  | 18,027,781                 | 1.67      | 1.73 | 2,039             |
| CF-Mekongga    | 4.38                   | 24,729,572                  | 10,800,000                  | 13,929,572                 | 1.29      | 2.03 | 1,565             |
| AWD-Ciherang   | 4.34                   | 24,479,724                  | 9,360,000                   | 15,119,724                 | 1.62      | 1.13 | 3,092             |
| AWD-Inpari 32  | 4.94                   | 27,894,007                  | 9,630,000                   | 18,264,007                 | 1.90      | 1.06 | 3,472             |
| AWD-Mekongga   | 4.36                   | 24,625,523                  | 9,990,000                   | 14,635,523                 | 1.47      | 1.65 | 2,032             |

Table 2. The net greenhouse gas balance (NGHGB) under different water management and rice cultivars, Pati, rainy season 2017-2018.

| Treatment          | GWP\(_{\text{soil}}\) | GWP\(_{\text{plant}}\) | NGHGB   |
|--------------------|-----------------------|------------------------|---------|
|                    | Kg CO\(_2\)-e ha\(^{-1}\) | Kg CO\(_2\)-e ha\(^{-1}\) | Kg CO\(_2\)-e ha\(^{-1}\) |
| CF-Ciherang        | 88                    | 12,242                 | -2,312  |
| CF-Inpari 32       | 84                    | 13,788                 | -5,033  |
| CF-Mekongga        | 81                    | 12,270                 | -3,456  |
| AWD-Ciherang       | 73                    | 12,183                 | -7,366  |
| AWD-Inpari 32      | 99                    | 13,059                 | -7,899  |
| AWD-Mekongga       | 92                    | 12,920                 | -5,809  |

4. Conclusions

Compared to CF, the AWD irrigation system significantly reduced GWP\(_{\text{soil}}\) when it combined the Ciherang, Inpari 32 and Mekongga rice cultivars by 51%, 40% and 19%, respectively. The combination of AWD irrigation and Inpari 32 rice cultivar was the highest net GHG balance among all treatments by 7,899 kg ha\(^{-1}\) and also was the highest profit by IDR 18.3 million ha\(^{-1}\). This study clearly suggests the possibility of reducing GHG emission from the paddy field through appropriate selection of water management and rice cultivars to achieve an economically feasible and technically as a mitigation option.

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