SAINS TANAH – Journal of Soil Science and Agroclimatology

Journal homepage: http://jurnal.uns.ac.id/tanah

Seasonal methane emissions and agronomic performance of Indonesia's high-yielding rice cultivars on the north coastal rice fields of Central Java, Indonesia

Rina Kartikawati[1,2], Budiastuti Kurniasih[1]*, Eka Tarwaca Susila Putra[1], Eko Hanudin[3], Noppol Arunrat[4]

[1] Department of Agronomy, Faculty of Agriculture, Universitas Gadjah Mada, Jalan Flora 1 Bulaksumur, Sleman 55281, Yogyakarta, Indonesia
[2] Indonesia Agricultural Environment Standardization Institute (IAESI), Ministry of Agriculture, Jalan raya Jakenan-Jaken, km 05, Jaken, Pati 59182 Central Java, Indonesia
[3] Department of Soil Science, Faculty of Agriculture, Universitas Gadjah Mada, Jalan Flora 1 Bulaksumur, Sleman 55281, Yogyakarta, Indonesia
[4] Faculty of Environment and Resource Studies, Mahidol University, Salaya, Phutthamonthon, Nakhon Pathom 73170, Thailand

ARTICLE INFO

Keywords:
Growth
Methane flux
Rice characteristic
Salinity
Yield

Article history
Submitted: 2024-03-22
Revised: 2024-07-30
Accepted: 2024-08-19
Available online: 2024-11-02
Published regularly: December 2024

* *Corresponding Author*
Email address: tuti_b@ugm.ac.id

ABSTRACT

Rice contributes significantly to methane emissions. In the north coastal region of Central Java Island, flooding irrigation for high-yielding rice cultivation is used throughout the rice-producing season to reduce the salinity effect. Information on methane emissions in coastal rice fields, particularly in salt-affected soil, is still limited. This study aimed to measure the methane emissions from different high-yielding rice varieties and examine the association with agronomic performance. The study site was in the Wedung district of Demak Regency, Central Java, and the research was carried out from November 2022 to March 2023. Eight rice cultivars—*Ciherang, Inpari 32, Inpari 34, Inpari 35, Biosalin 1, Biosalin 2, Inpari Unsoed 79, and Inpari 30*—were investigated. The experiment was designed as a randomized block with four replications. Methane gas samples were collected during the growing season in relation to rice stages. There were substantial differences in methane emissions among the eight rice varieties. Inpari 32, Ciherang, and Biosalin 1 had higher rice yields and lower yield-scale methane emissions than the other five rice varieties. Grain production and effective tiller number were significantly ($p<0.01$) and inversely linked to methane emissions. We found Inpari 32, Ciherang, and Biosalin 1 to be low-methane and high-yielding rice cultivars in salt-affected soil. These findings suggest that coastal farmers could use these rice varieties to help mitigate greenhouse gas emissions.

How to Cite: Kartikawati, R., Kurniasih, B., Putra, E.T.S., Eko Hanudin, E., Arunrat, N. (2024). Seasonal methane emissions and agronomic performance of Indonesia's high-yielding rice cultivars on the north coastal rice fields of Central Java, Indonesia. Sains Tanah Journal of Soil Science and Agroclimatology, 21(2): 135-144. https://doi.org/10.20961/stjssa.v21i2.88174

1. INTRODUCTION

Methane is a major greenhouse gas emitted by rice fields, particularly those with continually flooded irrigation. Rice production is among the largest anthropogenic contributors to methane production (Munawaroh et al., 2022), accounting for 10% of agricultural greenhouse gas emissions (Ranganathan et al., 2016). Rice plays a significant role in releasing methane due to its function as a substrate source for methanogen bacteria; in addition, it is a channel for the emission of methane gas from the soil to the atmosphere through the aerenchyma. This transport mechanism accounts for over 90% of the released methane (Butterbach-Bahl et al., 1997). The aerenchyma area and root lateral section are strongly associated with methane emissions. Rice cultivars with a large root area generate more aerenchyma area, which acts as an exhaust canal, elevating methane emissions (Kim et al., 2018). (Ardiarini et al., 2020) showed that larger cavities of root aerenchyma released more methane emissions. (Bharali et al., 2017), the size of the node's xylem vessels strongly correlates with seasonal cumulative methane emissions.

The amount of methane emitted is determined by the characteristics of a rice variety. Methane emissions have been shown to be positively connected with the tiller number but negatively correlated with the rice harvest index, root biomass, and panicle (Qin et al., 2015). Jiang et al. (2016) noted a substantial negative correlation between the number of spikelet and methane emissions during the reproductive stage. The larger rice panicles not only increased rice yields

STJSSA, p-ISSN 1412-3606 e-ISSN 2356-1424
http://dx.doi.org/10.20961/stjssa.v21i2.88174

but also reduced methane emissions. Most of the photosynthate is allocated to the panicle, reducing the quantity of photosynthate delivered to the roots and decreasing the amount of food source available to methanogenic bacteria. Kartikawati et al. (2021) found a significant positive connection between methane emissions and the number of tillers and panicles, as well as the rice yield and root biomass. Soremi et al. (2023) showed that the release of methane is driven by the aboveground biomass and root properties of hybrid rice cultivars. In comparison with the inbred variety and breeding line, hybrid rice cultivars consistently had the highest methane emissions at maturity. In line with Lee et al. (2023), there was a considerable connection between root biomass weight and the production of methane, particularly on the earlier transplanting date. Methane production was also affected by the rice growth period. Rice cultivars with longer growth periods produced higher total emissions (Habib et al., 2023; Win et al., 2021).

Indonesia is the world's biggest archipelago country, with around 281 million people in 2024 (BPS, 2020). The agricultural sector considers it important to produce sufficient food for the population. Unfortunately, coastal areas and small islands are endangered by rising seawater levels and seawater intrusion, which cause soil salinity and reduce crop production. Almost all rice cultivation in coastal rice fields, particularly in salt-affected soil, is conducted by continuous flooding. Flooding can alleviate salt stress throughout the growth season, but the anaerobic environment of rice fields can also promote methane production. Xu et al. (2015), Tariq et al. (2018), and Islam et al. (2022) demonstrated that continuous flooding in irrigated rice fields released a higher methane flux compared with alternate wetting and drying. Kaleeswari and Bell (2019) also observed that methane emissions were greater in thoroughly saturated soil.

Much research has been conducted on methane emissions, particularly in non-saline irrigated rice fields. Studies have explored both the amount and management of these emissions, including the use of rice cultivars (Pramono et al., 2021; Qin et al., 2015; Wihardjaka et al., 2020; Win et al., 2021). However, research that quantifies methane emissions among high-yielding rice cultivars in the coastal rice field is lacking. Saline rice fields are a unique environment in terms of methane emissions. In one study, increased electrical conductivity (EC) and lowered pH decreased methane emissions, but additional N fertilizer promoted methane production both in high and low EC environments (Datta et al., 2013). Therefore, we conducted a study in the coastal region of North Central Java to determine the level of methane emissions produced by saline-soil rice fields. The present study is one of the few that have examined the relationship between methane emissions and agronomic parameters among several rice cultivars in a coastal saline rice field. The main objective of this study was to measure the quantity of methane emitted by several high-yielding rice cultivars on the coastal rice field, particularly on salt-affected soil. We sought to identify a high-yielding, low-methane-emission rice cultivar from our study site that could reduce methane emissions from the agriculture sector.

2. MATERIAL AND METHODS

2.1. Study area

The study was conducted in the Wedung sub-district, Demak Regency, Central Java (6°47'58"S 110°36'26"E), located on the north coast of Java Island (Fig. 1). The altitude ranges from 0–3 meters above sea level. The temperature ranges from 26.7 – 30.4 °C. The rainy season spans October to May, and the highest precipitation occurs in February (692 mm). The soil is composed of clay (70%), silt (29%), and sand (1%).

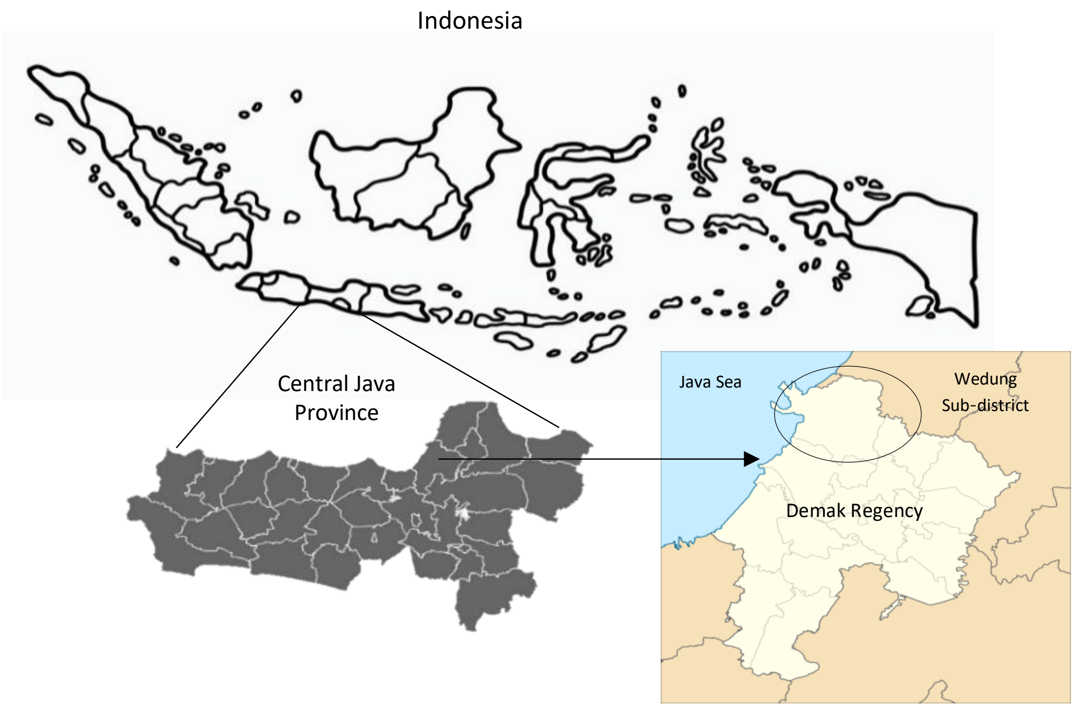
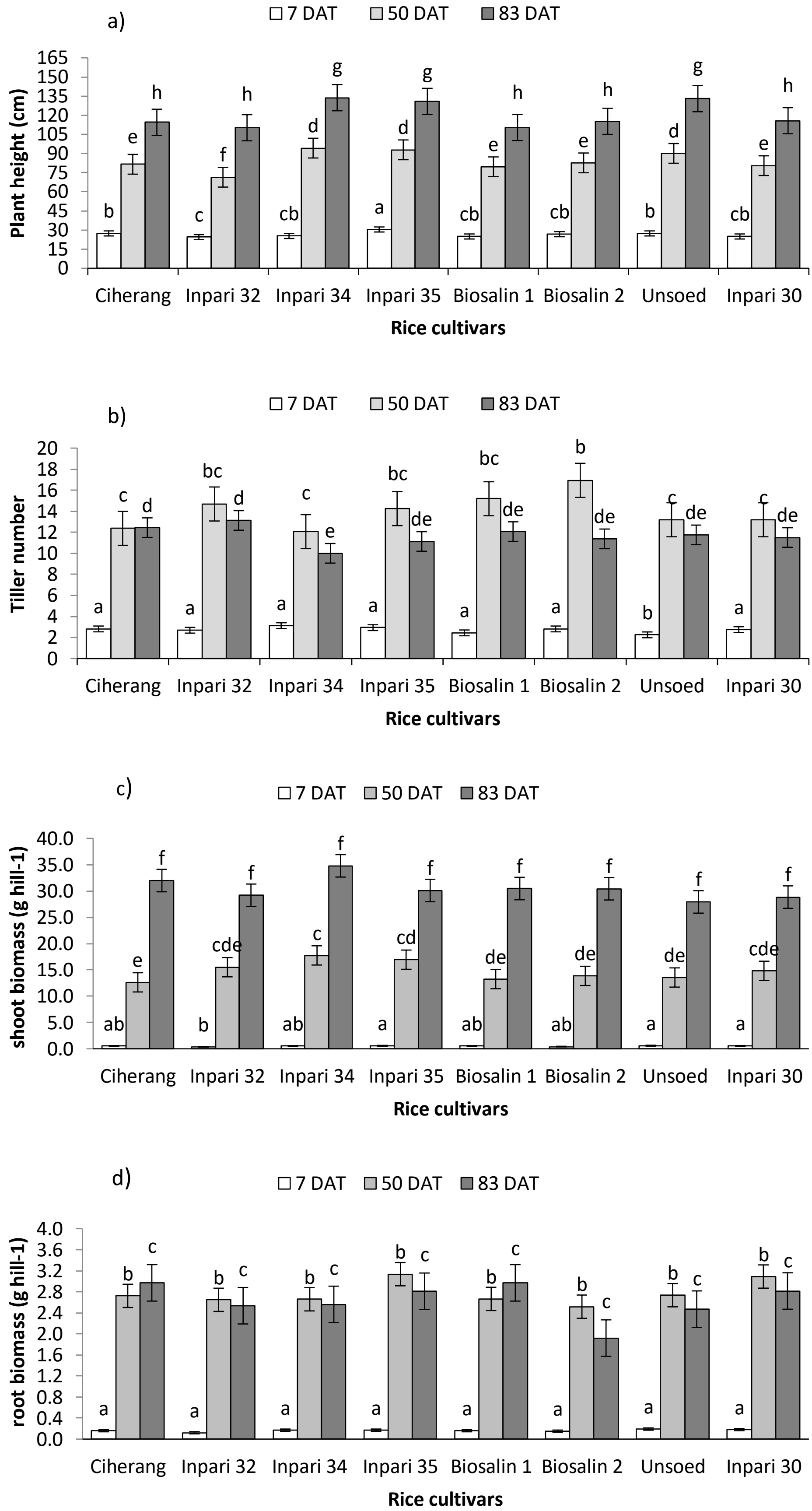


Figure 1. Location of field experiment in Wedung sub-district, Demak Regency, Central Java Province



Remarks: In the same-day observation, means followed by the same letter are not significantly different at the 5% level by Duncan's multiple range tests.

Figure 2. Rice cultivars characteristics a) plant height, b) tiller number, c) dry shoot biomass and d) dry root biomass during rice growing season on saline-affected rice field

2.2. Experimental design and field management

The field experiment was conducted from November 2022 to March 2023. The experiment was arranged as a randomized complete block design with four replications. There were 32 plots in total, and each field plot was 4.0 m x 5.0 m in area. Eight high-yielding rice cultivars from Indonesia, *Ciherang*, *Inpari 32*, *Inpari 34*, *Inpari 35*, *Biosalin 1*, *Biosalin 2*, *Unsoed 79*, and *Inpari 30*, were used in this study. The rice cultivars *Ciherang and Inpari 32* are commonly planted by farmers in irrigated rice fields and in the Wedung's coastal area. *Inpari 34, Inpari 35*, and *Inpari Unsoed 79* are salt-tolerant rice cultivars that are tolerant to salt stress during the seedling phase at 12 dS m^{-1}. Biosalin 1 and Biosalin 2 are also salt-tolerant rice cultivars that grow well in coastal rice fields, and *Inpari 30* is a water-submerged-tolerant rice cultivar. The total harvesting time periods for *Ciherang*, *Inpari 32*, *Inpari 34*, *Inpari 35*, *Biosalin 1*, *Biosalin 2*, *Unsoed 79*, and *Inpari 30* are 116, 120, 102, 106, 113, 107, 109, and 111 days, respectively (Romdon et al., 2014). In the present study, rice seedlings were transplanted 22 days after sowing; one seedling was planted per planting hole, and plant spacing was 20 cm x 20 cm. There was no border between different cultivars, but we provided a plant spacing of 70 cm as a border.

We applied nitrogen (N) in the form of urea (100 kg ha^{-1}), ammonium sulfate (ZA) (100 kg ha^{-1}), superphosphate (100 kg ha^{-1}), and NPK (100 kg ha^{-1}). Urea, superphosphate, and NPK were applied three times during the rice season (fibrous root emergence [7-15 DAT], 30 DAT, and the primordial phase). ZA was applied twice during the rice season, 50% as basal fertilizer and 50% as tiller fertilizer. Irrigation was performed with a water channel to bring fresh water during the rainy season.

2.3. Gas sample collection and analyses

Methane fluxes were measured five times during the rice season seven, 36, 50, 65, and 83 days after transplanting, that presented rice growth stage (vegetative, maximum of tiller, effective tiller, and reproductive) using the static chamber method. The dimensions of the static chamber were 50 cm long x 50 cm wide x 100 cm high. The sampling time interval was 5 minutes, and four samples were obtained from each plot. The temperature inside the static chamber was also recorded. Four hills of rice plants were covered with a chamber.

Methane concentrations in the samples were analyzed using a gas chromatograph-equipped flame ionization detector. The flux rate at the time of chamber closure was determined through Equation 1 described by Minamikawa et al. (2015).

$$E = \frac{dc}{dt}\ x\ \frac{Vch}{Ach}\ x\ \rho\ x\ \frac{273.2}{273.2+T} \quad [1]$$

where E = flux of methane (mg m^{-2} day^{-1}), dc/dt = concentration change over time of methane (ppm $menit^{-1}$), Vch = chamber volume (m^3), Ach = chamber area (m^2), p = gas density (0.717 kg m^{-3}), and T = average of temperature during gas sampling (^{o}C).

2.4. Plant sampling and processing

We also recorded agronomical parameters, including plant height, number of tillers, shoot and root dry weight, yield, and yield components.

2.5. Data analysis

We performed an analysis of variance to determine statistically significant differences between rice cultivars in the field site and conducted a multivariate analysis of variance using SPSS 20.

3. RESULTS

3.1. Agronomic characteristics of rice cultivars

We recorded certain characteristics of the rice cultivars, such as plant height, tiller number, shoot, and root biomass (Fig. 2). Rice characteristics varied among the eight rice cultivars studied. Plant height (Fig. 2a) was significantly different in the vegetative and generative phases (7, 50, and 83 DAT). The *Inpari 35* cultivar had a good response to growth, as shown by the highest plant height at 7 DAT (30.4 cm). At 50 DAT and 83 DAT, however, *Inpari 34*, *Inpari 35*, and *Unsoed 79* showed no differences among each other, and their values were significantly higher than those of other varieties. At 50 and 83 DAT, the number of tillers was notably different (Fig. 2b). At 50 DAT, the Biosalin 2 cultivar produced more tillers (17 tillers), but this reduced to 11 tillers at 83 DAT. Inpari 32 had the most tillers at 13 tillers. We found that *Inpari 32* produced a greater effective tiller number during rice growing, while *Inpari 34* generated the fewest tillers.

Shoot biomass differed significantly only at 7 DAT (Fig. 2c). On the first observation (7 DAT), the *Inpari 32* cultivar produced the least shoot and root biomass, with values that were significantly lower than those of *Ciherang, Biosalin 1,* and *Inpari 30*. However, at a later stage, no differences in shoot and root biomass among the cultivars were observed. All rice cultivars showed substantially increased root biomass at 50 DAT (more than 90% of root biomass at 7 DAT) (Fig. 2d), but the biomass decreased at 83 DAT. The Biosalin 2 cultivar showed the greatest drop in root biomass (63%) followed *by Inpari 30* (53%).

3.2. Variation in methane fluxes among cultivars

During the growth season, the seasonal methane fluxes among rice cultivars differed (Fig. 3). Methane flow patterns were similar in rice cultivars *Inpari 34* and *Unsoed 79*. When compared to others, both rice cultivars had larger methane fluxes (123.18 and 128.64 mg m^{-2} day^{-1}) in the early vegetative phase (8 DAT), but these values dropped dramatically on the active tiller (36 DAT). Methane fluxes surged throughout the generative period and gradually declined after harvest. *Inpari 34* and *Unsoed 7*9 were harvested at 98 and 101 DAT, respectively, which was earlier than the time period specified in the rice characteristic description. Meanwhile, the methane flux patterns of six other rice cultivars (*Ciherang*, *Inpari 32*, *Inpari 35*, *Biosalin 1*, *Biosalin 2*, and *Inpari 30*) were identical.

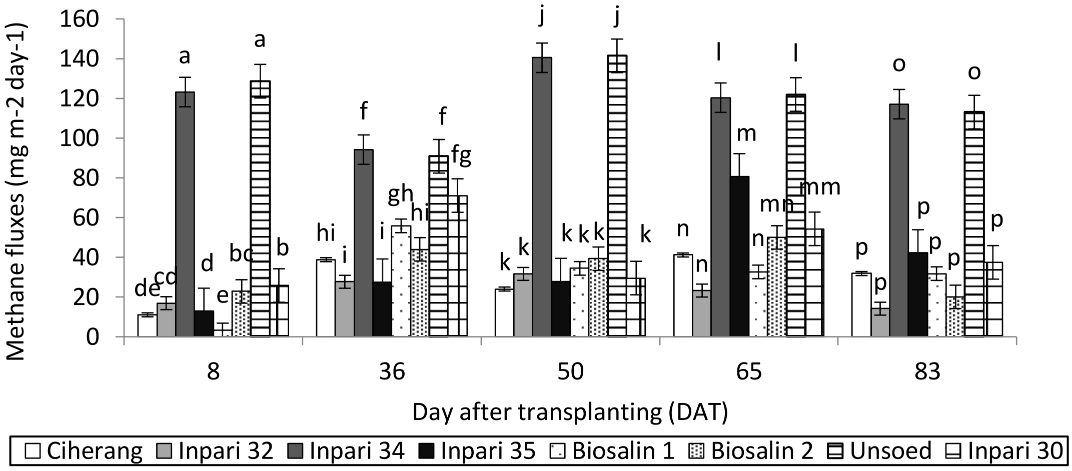


Figure 3. Seasonal variability in methane fluxes among various rice cultivars on salt-affected soil

Table 1. Total methane emissions and rice yield in the rice cultivars

Rice cultivars	Days to harvest (day)	Methane emission (kg ha^{-1}season^{-1})	Rice yield (t ha^{-1} season^{-1})	Yield-Scale Methane Emission (YSME) (kg methane t rice yield^{-1})
Ciherang	101	29.66bc	4.95a	6.1b
Inpari 32	101	22.97c	4.41ab	5.6b
Inpari 34	98	116.66a	2.79c	40.0a
Inpari 35	98	37.49bc	3.40bc	12.9b
Biosalin 1	101	31.94bc	4.20ab	8.0b
Biosalin 2	101	35.60bc	3.68ab	9.8b
Inpari Unsoed 79	101	120.37a	3.36bc	39.6a
Inpari 30	101	44.08b	4.41ab	10.0b

Remarks: In a column, means followed by the same letter are not significantly different at the 5% level by Duncan's multiple range test

In the early vegetative phase, methane fluxes were 11.04, 16.92, 12.88, 3.42, 22.82, and 25.79 mg m^{-2} day^{-1}, respectively, and rose significantly with rice stages, except for the maximum tiller. Methane fluxes increased throughout the generative period and then decreased during harvest.

Two distinct patterns clearly defined two categories of methane flow values: lower and higher than 80 mg m^{-2} day^{-1}. Methane fluxes from *Inpari 34* and *Unsoed 79* exceeded 80 mg m^{-2} day^{-1}. *Ciherang, Inpari 32*, *Inpari 35*, *Biosalin 1*, *Biosalin 2*, and *Inpari 30*, emitted less than 80 mg m^{-2} day^{-1} of methane flux. The methane flow patterns of the two groups were opposed. In the first observation, the two higher-methane flow cultivars had a high point, while the other rice cultivars had a low point. During the rice growing season, *Unsoed 79* (595.87 mg m^{-2}) had the highest cumulative methane flux, followed by *Inpari 34* (595.22 mg m^{-2}). *Inpari 30* (218.19 mg m^{-2}), *Inpari 35* (191.28 mg m^{-2}), *Biosalin 2* (179.21 mg m^{-2}), *Biosalin 1* (158.11 mg m^{-2}), and *Ciherang* (146.85 mg m^{-2}) were the next contributors to methane fluxes. *Inpari 32* had the lowest cumulative methane flux (113.61 mg m^{-2}).

Methane emissions differed significantly among the rice varieties (Table 1) and were ordered as follows: *Unsoed 79* > *Inpari 34* > *Inpari 30* > *Inpari 35* > *Biosalin 2* > *Biosalin 1* > *Ciherang* > *Inpari 32*. *Unsoed 79* produced the most methane emissions (120.37 kg ha^{-1}season^{-1}), followed by *Inpari 34* (116.66 kg ha^{-1}season^{-1}). *Inpari 32* produced the lowest methane emissions (22.97 kg ha^{-1}season^{-1}), followed by *Ciherang* (22.66 kg ha^{-1}season^{-1}), *Biosalin 1* (31.94 kg ha^{-1}season^{-1}), *Biosalin 2* (35.60 kg ha^{-1}season^{-1}), *Inpari 35* (37.49 kg ha^{-1}season^{-1}), and *Inpari 30* (44.08 kg ha^{-1}season^{-1}).

Seasonal rice grain yield also differed significantly among the cultivars (Table 1). The rice cultivar *Ciherang* had the highest average yield with a value of 4.95 t ha^{-1} season^{-1}, followed by *Inpari 32* and *Inpari 30* (4.41 t ha^{-1}season^{-1}) and *Biosalin 1* (4.20 t ha^{-1}season^{-1}). The lowest rice grain yield was observed in *Inpari 34* (2.79 t ha^{-1}season^{-1}). We also calculated yield-scaled methane emission (YSME), which is the relationship between methane emission and grain production. *Inpari 32, Ciherang, Biosalin 1,* and *Biosalin 2* showed lower YSME potential. Inpari 32 had the lowest methane emissions while producing a high rice grain yield. *Ciherang* shows potential as a low-methane-emission rice cultivar, as it produced the maximum rice grain production while emitting the least amount of methane emission.

3.3. Correlation between the agronomic characteristic of rice cultivars and methane emissions

There was a positive correlation between dry shoot biomass and all agronomic characteristics except for effective tiller number (Table 2). Dry root biomass was positively correlated with dry shoot biomass and rice yield but negatively correlated with plant height and effective tiller number. Plant height showed a positive correlation only with shoot biomass. Rice yield was supported by root and shoot biomass and correlated strongly with the effective tiller number.

Methane emissions and rice cultivar growth parameters were strongly correlated. Rice grain production and the effective tiller number were both significantly and adversely connected with methane emissions. Methane emissions were also strongly linked with plant height. The dry weight of shoot biomass was favorably connected to root biomass, plant height, and grain production. The effective tiller number and grain yield had a substantial positive correlation. We also found a negative relationship between plant height and root biomass, the effective tiller number, and grain yield.

We used structural equation modeling to investigate the direct and indirect effects of agronomic characteristics on methane emissions (Fig. 4). Rice yield was directly affected by shoot biomass and effective tillering but not by root biomass or plant height. Only plant height had a positive direct impact on methane emissions.

4. DISCUSSION

We identified a unique trend for cultivars *Inpari 34* and *Unsoed 79*, which had higher methane fluxes in the early vegetative phase (Fig. 3). The methane flux generally increased during the rice growing season and steadily declined after harvest (Ha et al., 2023; Islam et al., 2022)). The EC value positively affected the methane fluxes of *Inpari 34* and *Unsoed 79*, which suggested that the EC could lead to methane production in these cultivars. However, it had a negative effect on the six other cultivars (*Ciherang*, *Inpari 32*, *Inpari 35*, *Biosalin 1*, *Biosalin 2*, and *Inpari 30*). The EC value was 3.31 dS m^{-1} at 7 DAT and decreased at 36 DAT (1.84 dS m^{-1}). It subsequently increased at 50 and 65 DAT, with values of 2.10 and 2.13 dS m^{-1}, respectively, before decreasing at 83 DAT (1.89 dS m^{-1}). Tong et al. (2017) found that increasing salinity boosted methane and nitrous oxide emissions by accelerating organic carbon decomposition and nitrogen transformation rates. Rice cultivar parameters, such as tiller number, plant height, biomass weight, and rice production, all contributed to the quantity of methane flux in the present research.

Ciherang and *Inpari 32* had lower methane emissions than other cultivars (Table 1) due to their higher effective tiller numbers compared with other cultivars (Fig. 2b), indicating less organic matter loss during rice cultivation. As a result, the soil contained less substrate to support methane synthesis. *Ciherang* and *Inpari 32* produced more shoot and root biomass than other cultivars, and we found a negative relationship between above- and below-ground biomass and emissions. Our findings contradicted those of Wihardjaka et al. (2020), who showed a considerable positive correlation between plant biomass and methane emissions, particularly during the panicle start stage. In saline soil, we expected that nutrients absorbed by the root would be allocated to increase shoot biomass and hence produce assimilate, which would transfer to rice grain. The *Ciherang* cultivar had the largest root biomass (20.08 g $hill^{-1}$) and produced the most rice grain. Meng et al. (2021) demonstrated that shoot and root growth accounted for rice yield in saline fields.

The higher methane emissions of *Inpari 34* and *Unsoed 79* could be attributable to their higher plant heights compared with other cultivars. We found a strong connection between methane emissions and plant height (Fig. 4). Stagnant flooding during rice cultivation increased the number of aerenchyma gas spaces per tiller and decreased root oxidation activity (Kuanar et al., 2017). In their study, Bhattacharyya et al. (2019) noted that aerenchyma space and the ratio of aerenchyma space to total space were strongly (positively) linked to the rate of methane emissions.

Table 2. The matrix correlation between methane emission and rice cultivars characteristic

	Methane emission (kg ha^{-1} $season^{-1}$)	Dry shoot biomass (g)	Dry Root biomass (g)	Plant height (cm)	Effective tiller number	Yield (t ha^{-1})
Methane emission	1	.055	-.085	.684**	-.567*	-.444*
Dry shoot biomass	.055	1	.237	.232	-.079	.095
Dry root biomass	-.085	.237	1	-.084	-.008	.031
Plant height	.684**	.232	-,084	1	-.304	-.356*
Effective tiller number	-.567*	-.079	-.008	-.304	1	.358*
Yield	-.444*	.095	.031	-.356*	.358*	1

Remarks: **. Correlation is significant at the 0.01 level (2-tailed); *. Correlation is significant at the 0.05 level (2-tailed).

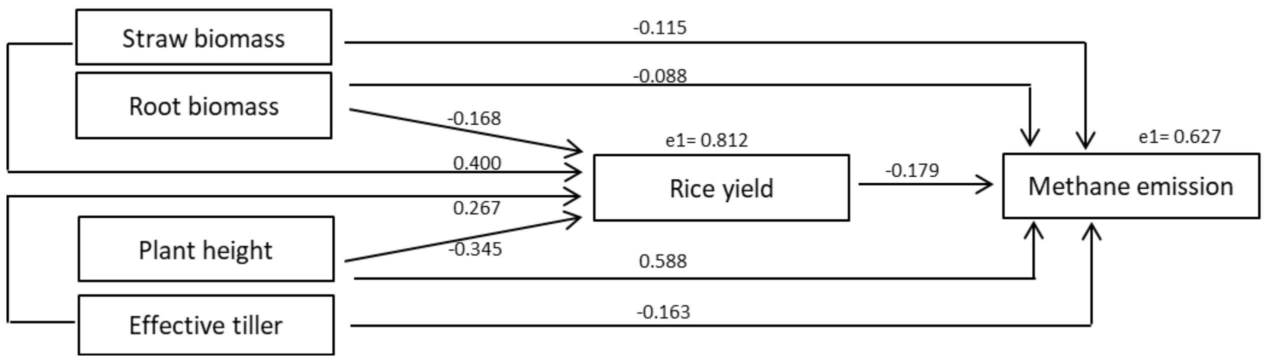


Figure 4. Relationship between agronomic performance and methane emission among rice cultivars.

Furthermore, a greater oxidation power in the rhizosphere lowers methane input by either boosting methane oxidation or suppressing methanogenesis. Unfortunately, plant height was negatively correlated with effective tiller number, filled grain, and rice yield in the present research. As a result, *Inpari 34* and *Unsoed 79* yielded less rice than others, at 2.79 and 3.36 t ha^{-1}, respectively (Table 2). Rumanti et al. (2020) found that maintaining water depth from 30 DAT to maturity stage by 5 cm to 60–70 cm enhanced plant height rather than decreasing panicle length and emptied grain per panicle. Plant heights greater than 140 cm were resistant to lodging during stagnant flooding, resulting in a 48% loss in yield during the dry season and an 88% reduction during the wet season in a study by Kato et al. (2019). These results align with our data showing a negative association between plant height and rice yield.

The cultivars *Ciherang* and *Inpari 32* had lower methane emissions but higher rice yields than other cultivars, along with a lower YSME, at 6.1 and 5.6 kg methane t $yield^{-1}$, respectively. During the growing season, a 1-ton yield of *Ciherang* and *Inpari 32* emitted approximately 6.1 and 5.6 kg of methane, respectively. *Ciherang* and *Inpari 32* were, therefore, low-methane and high-yielding rice cultivars in salt-affected soil, especially when leached by freshwater. *Inpari 34* and *Unsoed 79*, in contrast, had greater YSMEs, at 40.0 and 39.6 kg methane t $yield^{-1}$, respectively. We found that rice yield had a strong negative correlation with methane emissions. Rice yield was supported by above- and below-ground biomass, as well as tiller number, which correlated positively (Table 2). Tillers in our study were productive in producing panicles. More photosynthates were delivered to the sink organ, resulting in enhanced grain yield. According to Baruah et al. (2010), enhanced photosynthetic partitioning in growing panicles and grains, as well as at the grain-filling stage, could explain the higher grain yields in rice cultivars with lower methane emissions. Kwon et al. (2023) discovered that increasing sink strength by raising photosynthate distribution to grain instead of root resulted in a lower root exudate release, leading to low methane production. Surprisingly, both *Inpari 32* and *Ciherang* are widely grown by farmers along the north coast, suggesting that farmers unconsciously contribute to reducing methane emissions.

Overall, methane emissions were lower in the saline-affected soil than in the unaffected soil. Methane production rates were negligible (1 mg methane m^{-2} h^{-1}) at salinity concentrations greater than 18 ppt (29 mS cm^{-1}), most likely because were defeated by sulphate-reducing bacteria (Olsson et al., 2015). In the present study, the EC of soil ranged from 1.49 to 5.13 dS m^{-1} during rice growing, and total methane emissions were in the range of 23 – 120 kg ha $season^{-1}$, which was lower than in the unaffected soil. Methane emissions from rainfed rice fields were 168 – 285 kg ha^{-1} $season^{-1}$ (Kartikawati et al., 2021) and 141 – 293 kg ha^{-1} $season^{-1}$ (Pramono et al., 2021). Methane emissions were limited in salt-affected soil, with decreased soil microbial metabolism and population (Nguyen et al., 2020; Vo et al., 2018).

We found that the total concentrations of exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) were inversely linked with methane emissions. In contrast, all Na^+, K^+, Ca^{2+}, and Mg^{2+} concentrations were higher in the coastal area than in the terrestrial area. It has been proposed that the salt content of the soil is a crucial component in reducing methane emissions from coastal rice paddy soils (Sun et al., 2018). The Na^+ concentration in our study site was 7.48 cmol(+) kg^{-1}. Pam Hazelton (2007) divided Na^+ in soil into five categories ranging from very low (0 – 0.1 cmol(+) kg^{-1}) to extremely high (> 2 cmol(+) kg^{-1}). Our results concurred with those of Datta et al. (2013), who showed that methane fluxes from saline rice fields were substantially lower than those from irrigated inland non-saline rice fields. The total seasonal methane fluxes ranged between 120 and 264 kg ha^{-1} $season^{-1}$. However, Ha et al. (2023) found that rice fields with salt intrusion produced more methane emissions annually compared with freshwater rice fields, rice-vegetable rotation, and continuous vegetables. In our study, the number of tillers during maximum tiller development was 14–19, and this number decreased at the generative phase by 10–13 tillers. Therefore, around 20% of the leaves were deciduous, and they could potentially contribute to methane emissions by acting as a substrate. Qu et al. (2019) found that salt concentration slows the degradation of organic carbon and dissolved organic carbon, which suggests why our location showed lower methane emissions during rice cultivation.

We found that rice cultivars grown in salt-affected soil could survive during rice growing. In a study by Kusuma et al. (2021), the limit tolerance of crop to salinity was 4 dS m^{-1}. Consistent water availability and good water management during rice cultivation were key factors in supporting plant survival in our study site. The water level of our study site was kept sufficiently high (15 – 17 cm) to prevent salinity from rising. Hafez et al. (2015) stated that flooded water benefits plant growth and is required for draining salts from the profile soil. Regular irrigation removes salts more effectively. In our study, the early vegetative phase, notably 10 DAT or before first fertilization, was an essential moment for rice growth. Seedlings faced the challenges of inadequate soil nourishment and salt. As a result, rice cultivars only developed 2 to 3 tillers at 8 DAT. According to Hussain et al. (2018), one of the most essential stages for rice crop stand formation and limiting rice output in salt-affected soil is the growth of transplanted seedlings.

In this study, *Inpari 32* had lower methane emissions (22.97 kg $ha^{-1}season^{-1}$) compared with rainfed rice fields (non-saline soil). Interestingly, rice yield from *Inpari 32* in both saline (the present study) and non-saline rice fields (Kartikawati et al., 2021) was consistently high. Therefore, *Inpari 32* shows potential as a low-methane-emission-yielding rice cultivar for coastal rice fields. Thus, based on this research, coastal farmers can contribute to reducing greenhouse gas emissions by using low-methane, high-yielding rice varieties during rice cultivation.

5. CONCLUSION

Our findings revealed that eight rice cultivars differed significantly in terms of methane emissions. *Inpari 32, Ciherang*, and *Biosalin 1* produced a high rice yield and had lower YSME values than the five other cultivars (*Inpari 34, Inpari 35, Biosalin 2, Unsoed 79*, and *Inpari 30*). Lower YSME rice varieties showed a positive correlation between tiller number and above- and below-ground biomass. This is because the sink organ receives more photosynthates, increasing grain yield. A higher effective tiller number, which indicates less loss of organic matter, is the trigger for lower methane emissions. Further investigation into high-yielding, low-methane-emission rice cultivars in saline soil could support the mission to reduce greenhouse gases. Farmers in coastal areas have also contributed to mitigating greenhouse gas emissions using *Inpari 32* and *Ciherang*.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

References

Ardiarini, N. R., Arisandi, F. D., & Setyanto, P. (2020). Characteristics of rice plant with low methane emission. *Ecology Environment and Conservartion*, *26*, 150-155. https://www.envirobiotechjournals.com/issues/article_abstract.php?aid=10440&iid=301&jid=3

Baruah, K. K., Gogoi, B., & Gogoi, P. (2010). Plant physiological and soil characteristics associated with methane and nitrous oxide emission from rice paddy. *Physiology and Molecular Biology of Plants*, *16*(1), 79-91. https://doi.org/10.1007/s12298-010-0010-1

Bharali, A., Baruah, K. K., & Gogoi, N. (2017). Potential option for mitigating methane emission from tropical paddy rice through selection of suitable rice varieties. *Crop and Pasture Science*, *68*(5), 421-433, 413. https://doi.org/10.1071/CP16228

Bhattacharyya, P., Dash, P. K., Swain, C. K., Padhy, S. R., Roy, K. S., Neogi, S., . . . Mohapatra, T. (2019). Mechanism of plant mediated methane emission in tropical lowland rice. *Science of The Total Environment*, *651*, 84-92. https://doi.org/10.1016/j.scitotenv.2018.09.141

BPS. (2020). *Statistical year book of Indonesia*. BPS - Statistics Indonesia. https://www.bps.go.id/id/publication/2020/04/29/e9011b3155d45d70823c141f/statistik-indonesia-2020.html

Butterbach-Bahl, K., Papen, H., & Rennenberg, H. (1997). Impact of gas transport through rice cultivars on methane emission from rice paddy fields. *Plant, Cell & Environment*, *20*(9), 1175-1183. https://doi.org/10.1046/j.1365-3040.1997.d01-142.x

Datta, A., Yeluripati, J. B., Nayak, D. R., Mahata, K. R., Santra, S. C., & Adhya, T. K. (2013). Seasonal variation of methane flux from coastal saline rice field with the application of different organic manures. *Atmospheric Environment*, *66*, 114-122. https://doi.org/10.1016/j.atmosenv.2012.06.008

Ha, L. T. T., An, N. T., Ha, N. T., Zhou, M., Brüggemann, N., & Cong, V. H. (2023). Greenhouse gas emissions from agricultural land use in the coastal area of Red River Delta. *International Journal of Environmental Science and Technology*, *20*(11), 12511-12520. https://doi.org/10.1007/s13762-023-04847-3

Habib, M. A., Islam, S. M. M., Haque, M. A., Hassan, L., Ali, M. Z., Nayak, S., . . . Gaihre, Y. K. (2023). Effects of Irrigation Regimes and Rice Varieties on Methane Emissions and Yield of Dry Season Rice in Bangladesh. *Soil Systems*, *7*(2), 41. https://doi.org/10.3390/soilsystems7020041

Hafez, E. M., Abou El Hassan, W. H., Gaafar, I. A., & Seleiman, M. F. (2015). Effect of gypsum application and irrigation intervals on clay saline-sodic soil characterization, rice water use efficiency, growth, and yield. *Journal of Agricultural Science*, *7*(12), 208. https://doi.org/10.5539/jas.v7n12p208

Hussain, M., Ahmad, S., Hussain, S., Lal, R., Ul-Allah, S., & Nawaz, A. (2018). Chapter Six - Rice in Saline Soils: Physiology, Biochemistry, Genetics, and Management. In D. L. Sparks (Ed.), *Advances in Agronomy* (Vol. 148, pp. 231-287). Academic Press. https://doi.org/10.1016/bs.agron.2017.11.002

Islam, S. M. M., Gaihre, Y. K., Islam, M. R., Khatun, A., & Islam, A. (2022). Integrated Plant Nutrient Systems Improve Rice Yields without Affecting Greenhouse Gas Emissions from Lowland Rice Cultivation. *Sustainability*, *14*(18), 11338. https://doi.org/10.3390/su141811338

Jiang, Y., Tian, Y., Sun, Y., Zhang, Y., Hang, X., Deng, A., . . . Zhang, W. (2016). Effect of rice panicle size on paddy field CH4 emissions. *Biology and Fertility of Soils*, *52*(3), 389-399. https://doi.org/10.1007/s00374-015-1084-2

Kaleeswari, R., & Bell, R. (2019). Greenhouse gas Emissions in Saline and Waterlogged. *Malaysian Journal of Soil Science*, *23*. https://www.msss.com.my/mjss/Full%20Text/vol23/V23_15.pdf

Kartikawati, R., Ariani, M., Wihardjaka, A., & Setyanto, D. (2021). Characteristic of Rice Variety for Low Greenhouse Gases (GHGs) Emission in Facing the Challenges of Climate Change and National Food Security. Proceedings of PERIPI, Bogor, Indonesia.

Kato, Y., Collard, B. C. Y., Septiningsih, E. M., & Ismail, A. M. (2019). Increasing flooding tolerance in rice: combining tolerance of submergence and of stagnant flooding. *Annals of Botany*, *124*(7), 1199-1209. https://doi.org/10.1093/aob/mcz118

Kim, W.-J., Bui, L. T., Chun, J.-B., McClung, A. M., & Barnaby, J. Y. (2018). Correlation between methane (CH4) emissions and root aerenchyma of rice varieties. *Plant Breeding and Biotechnology*, *6*(4), 381-390. https://doi.org/10.9787/PBB.2018.6.4.381

Kuanar, S. R., Ray, A., Sethi, S. K., Chattopadhyay, K., & Sarkar, R. K. (2017). Physiological Basis of Stagnant Flooding Tolerance in Rice. *Rice Science*, *24*(2), 73-84. https://doi.org/10.1016/j.rsci.2016.08.008

Kusuma, E. W. W., Maas, A., Utami, S. N. H., & Maftuah, E. (2021). Effects of rice husk biochar and raised bed on CO2 flux and shallot (Allium cepa L.) production on peatland. *Sains Tanah - Journal of Soil Science and*

Agroclimatology, *18*(2), 159-165. https://doi.org/10.20961/stjssa.v18i2.47974

Kwon, Y., Lee, J.-Y., Choi, J., Lee, S.-M., Kim, D., Cha, J.-K., . . . Ryu, C.-M. (2023). Loss-of-function gs3 allele decreases methane emissions and increases grain yield in rice. *Nature Climate Change*, *13*(12), 1329-1333. https://doi.org/10.1038/s41558-023-01872-5

Lee, J.-H., Lee, J.-Y., Kang, Y.-G., Kim, J.-H., & Oh, T.-K. (2023). Evaluating methane emissions from rice paddies: A study on the cultivar and transplanting date. *Science of The Total Environment*, *902*, 166174. https://doi.org/10.1016/j.scitotenv.2023.166174

Meng, T., Zhang, X., Ge, J., Chen, X., Yang, Y., Zhu, G., . . . Dai, Q. (2021). Agronomic and physiological traits facilitating better yield performance of japonica/indica hybrids in saline fields. *Field Crops Research*, *271*, 108255. https://doi.org/10.1016/j.fcr.2021.108255

Minamikawa, K., Tokida, T., Sudo, S., Padre, A., & Yagi, K. (2015). Guidelines for measuring CH4 and N2O emissions from rice paddies by a manually operated closed chamber method. *National Institute for Agro-Environmental Sciences, Tsukuba, Japan*, *76*. https://globalresearchalliance.org/wp-content/uploads/2018/02/Guidelines-for-Measuring-CH4-and-N2O-Emissions-from-Rice-Paddies-by-Manually-Operated-Closed-Chamber-Method-2015.pdf

Munawaroh, U., Komariah, K., Ariyanto, D. P., Zaki, M. K., & Noda, K. (2022). Estimates of methane and nitrous oxide emission from a rice field in Central Java, Indonesia, based on the DeNitrification DeComposition model. *Sains Tanah - Journal of Soil Science and Agroclimatology*, *19*(1), 1-11. https://doi.org/10.20961/stjssa.v19i1.56928

Nguyen, B. T., Trinh, N. N., & Bach, Q.-V. (2020). Methane emissions and associated microbial activities from paddy salt-affected soil as influenced by biochar and cow manure addition. *Applied Soil Ecology*, *152*, 103531. https://doi.org/10.1016/j.apsoil.2020.103531

Olsson, L., Ye, S., Yu, X., Wei, M., Krauss, K. W., & Brix, H. (2015). Factors influencing CO₂ and CH₄ emissions from coastal wetlands in the Liaohe Delta, Northeast China. *Biogeosciences*, *12*(16), 4965-4977. https://doi.org/10.5194/bg-12-4965-2015

Pam Hazelton, B. M. (2007). *Interpreting Soil Test Results: What do all the Numbers mean?* CSIRO Publishin. https://doi.org/10.1071/9780643094680

Pramono, A., Adriany, T. A., Susilawati, H. L., & Sutriadi, M. T. (2021). Effects of rice cultivar on the net greenhouse gas emission under continuous flooding and alternate wetting and drying irrigations in paddy field. *IOP Conference Series: Earth and Environmental Science*, *648*(1), 012095. https://doi.org/10.1088/1755-1315/648/1/012095

Qin, X., Li, Y. e., Wang, H., Li, J., Wan, Y., Gao, Q., . . . Fan, M. (2015). Effect of rice cultivars on yield-scaled methane emissions in a double rice field in South China. *Journal of Integrative Environmental Sciences*, *12*(sup1), 47-66. https://doi.org/10.1080/1943815X.2015.1118388

Qu, W., Li, J., Han, G., Wu, H., Song, W., & Zhang, X. (2019). Effect of salinity on the decomposition of soil organic carbon in a tidal wetland. *Journal of Soils and Sediments*, *19*(2), 609-617. https://doi.org/10.1007/s11368-018-2096-y

Ranganathan, J., Vennard, D., Waite, R., Lipinski, B., Searchinger, T., & Dumas, P. (2016). *Shifting Diets for a Sustainable Food Future*. World Resources Institute. https://www.wri.org/research/shifting-diets-sustainable-food-future

Romdon, A. S., Kurniyati, E., Bahri, S., & Pramono, J. (2014). *Kumpulan DESKRIPSI VARIETAS PADI*. Central Java Assesment Institute for Agricultural Technology. Indonesian Agency for Agricultural Research and Development (IAARD). https://repository.pertanian.go.id/handle/123456789/12696

Rumanti, I. A., Sitaresmi, T., & Nugraha, Y. (2020). Rice tolerance variation to long-term stagnant flooding and germination ability under an-aerobic environment. *IOP Conference Series: Earth and Environmental Science*, *423*(1), 012048. https://doi.org/10.1088/1755-1315/423/1/012048

Soremi, P. A. S., Chirinda, N., Graterol, E., & Alvarez, M. F. (2023). Potential of rice (Oryza sativa L.) cultivars to mitigate methane emissions from irrigated systems in Latin America and the Caribbean. *All Earth*, *35*(1), 149-157. https://doi.org/10.1080/27669645.2023.2207941

Sun, M., Zhang, H., Dong, J., Gao, F., Li, X., & Zhang, R. (2018). A comparison of CH4 emissions from coastal and inland rice paddy soils in China. *CATENA*, *170*, 365-373. https://doi.org/10.1016/j.catena.2018.06.035

Tariq, A., Jensen, L. S., Sander, B. O., de Tourdonnet, S., Ambus, P. L., Thanh, P. H., . . . de Neergaard, A. (2018). Paddy soil drainage influences residue carbon contribution to methane emissions. *Journal of Environmental Management*, *225*, 168-176. https://doi.org/10.1016/j.jenvman.2018.07.080

Tong, C., Cadillo-Quiroz, H., Zeng, Z. H., She, C. X., Yang, P., & Huang, J. F. (2017). Changes of community structure and abundance of methanogens in soils along a freshwater–brackish water gradient in subtropical estuarine marshes. *Geoderma*, *299*, 101-110. https://doi.org/10.1016/j.geoderma.2017.03.026

Vo, T. B. T., Wassmann, R., Tirol-Padre, A., Cao, V. P., MacDonald, B., Espaldon, M. V. O., & Sander, B. O. (2018). Methane emission from rice cultivation in different agro-ecological zones of the Mekong river delta: seasonal patterns and emission factors for baseline water management. *Soil Science and Plant Nutrition*, *64*(1), 47-58. https://doi.org/10.1080/00380768.2017.1413926

Wihardjaka, A., Yulianingsih, E., & Yulianingrum, H. (2020). Methane flux from high-yielding Inpari rice varieties in Central Java, Indonesia. *Sains Tanah - Journal of Soil*

Science and Agroclimatology, *17*(2), 129-134. https://doi.org/10.20961/stjssa.v17i2.42729

Win, E. P., Win, K. K., Bellingrath-Kimura, S. D., & Oo, A. Z. (2021). Influence of rice varieties, organic manure and water management on greenhouse gas emissions from paddy rice soils. *PLOS ONE*, *16*(6), e0253755. https://doi.org/10.1371/journal.pone.0253755

Xu, Y., Ge, J., Tian, S., Li, S., Nguy-Robertson, A. L., Zhan, M., & Cao, C. (2015). Effects of water-saving irrigation practices and drought resistant rice variety on greenhouse gas emissions from a no-till paddy in the central lowlands of China. *Science of The Total Environment*, *505*, 1043-1052. https://doi.org/10.1016/j.scitotenv.2014.10.073