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REVIEW

Rice crop management to increase productivity and reduce methane emissions in Indonesia

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ABSTRACT

Rice (*Oryza sativa* L.) is the staple food of Indonesia, and its production must continue to increase to meet growing demand driven by population growth, high dependency on rice as a carbohydrate source, and inefficient consumption patterns. However, rice cultivation faces several critical challenges, including the reduction of agricultural land, land-use conversion, declining soil fertility, a shrinking number of farming households, and increased pest pressure. Efforts to enhance rice productivity while addressing environmental concerns have focused on the adoption of effective and sustainable crop management practices. Irrigated rice fields contribute the highest yields due to their superior productivity and cropping index, but they also serve as major sources of methane (CH_4) emissions—primarily released through aerenchyma tissues, ebullition, and diffusion. This paper explores sustainable crop management strategies aimed at reducing CH_4 emissions while maintaining or improving productivity. These strategies include the selection of low-emission rice varieties, optimization of planting systems, and improved land-use planning across various agroecosystems, including irrigated fields, rainfed fields, tidal swamps, freshwater swamps, and dryland areas. By integrating these approaches, rice cultivation in Indonesia can move toward greater environmental sustainability and long-term food security.

Key words: Crop management, emission index, methane gas emission, *Oryza sativa*, rice productivity.

INTRODUCTION

The development of agriculture in a country is shaped by various strategic environmental changes, both internal and external. These include factors such as population growth, rising living standards, improved quality of life, and increasing global demand for food. In the context of Indonesia, such factors have contributed to efforts aimed at increasing rice availability to meet national and global food security needs.

The majority of Indonesia’s rice (*Oryza sativa* L.) demand is currently met through the use of irrigated paddy fields, which offer higher productivity (Tirtalistyani et al., 2022). However, the extent of these lands has been steadily declining due to increasing development pressures (Hatta et al., 2023). On the island of Java, nearly

90% of technically irrigated paddy fields have been converted for non-agricultural purposes such as residential housing, roads, sports facilities, and industrial zones (Daris et al., 2018). If this trend continues, it poses a serious threat to Indonesia's food sovereignty (Ivanka et al., 2024) and to the livelihoods and well-being of farmers (Nurliani and Rosada, 2016). To ensure long-term rice availability, it is therefore essential to optimize the use of alternative agroecosystems, including tidal swamps, freshwater swamps, rainfed fields, and dryland areas.

The future development of rice cultivation should not be focused solely on achieving high productivity, but must also consider environmental sustainability and food security (Amini et al., 2020). According to Saha et al. (2022), rice cultivation is a potential contributor to CH_4 gas emissions. Research indicates that approximately 90% of CH_4 produced in paddy fields is released into the atmosphere through plant aerenchyma tissues, with the remaining emissions occurring via ebullition (8%-9%) and diffusion (1%-2%).

Research on CH_4 emissions from rice cultivation in Indonesia has shown that emission potential is significantly influenced by the choice of rice varieties (Slameto et al., 2024). In addition to varietal differences, several other factors contribute to CH_4 production, including crop management systems (Paramitha, 2023), planting methods (Susilawati et al., 2019), plant spacing (Abduh et al., 2020), and cropping systems (Susilastuti et al., 2018). Furthermore, the level of CH_4 emissions is also affected by land type (Ariani et al., 2021) and seasonal variation (Kartikawati et al., 2024).

Efforts to reduce CH_4 emissions from rice cultivation in paddy fields have been widely implemented. These initiatives aim not only to mitigate greenhouse gas emissions but also to sustain—and in some cases, enhance—rice productivity. Crop management practices play a central role in achieving these dual objectives by applying targeted interventions to minimize CH_4 emissions without compromising yield. Such practices are adapted to various agroecosystems, including irrigated fields, rainfed areas, drylands, tidal swamps, and freshwater swamps. Key strategies include the selection of low-emission rice varieties, improved crop and planting management systems, optimized planting methods and spacing, and seasonal adjustments. These technologies collectively provide a comprehensive framework for sustainable rice cultivation.

This paper explores integrated and sustainable strategies for rice crop management, emphasizing the adoption of low-emission rice varieties, improved planting techniques, and effective land-use planning across diverse rice-growing environments, included irrigated fields, rainfed fields, tidal swamps, freshwater swamps, and dryland areas.

DEVELOPMENT OF ENVIRONMENTALLY FRIENDLY RICE FARMING IN INDONESIA

Rice production in Indonesia

Indonesia must continue to enhance its rice production capacity in response to evolving strategic environmental conditions. This need is further driven by the country's high dependence on rice as a staple carbohydrate source and the relatively low efficiency of rice consumption. However, several critical challenges hinder efforts to increase rice availability. These include: (1) The ongoing shrinkage of agricultural land, (2) land conversion and competition for land use, (3) declining soil fertility, (4) a reduction in the number of farming households, (5) deterioration of agricultural infrastructure, (6) increasing incidence of pest and disease outbreaks, and (7) issues related to agricultural spatial planning (Lestari, 2022; Manalu et al., 2022).

In 2021, Indonesia's rice production reached 54 415 294 t, harvested from a total area of 10 411 801 ha (Statistics Indonesia, 2022). This output translated into 31 356 017 t milled rice. Compared to 2021, both paddy and rice production experienced declines of 233 908 and 140 730 t, respectively, primarily due to a reduction in harvested area by 245 474 ha. Despite this decrease, national rice production remained sufficient to meet domestic demand. The majority of Indonesia's rice continues to be produced in paddy fields located on the island of Java, followed by contributions from Sumatra, Sulawesi, and Kalimantan.

Rice production in Indonesia is derived from various agroecosystems, including irrigated fields, rainfed fields, dryland areas, tidal swamps, and freshwater swamps (Sulaiman et al., 2019). Among these, irrigated fields contribute the most to national rice output, followed by rainfed fields, tidal swamps, freshwater swamps, and, lastly, dryland areas. The dominant contribution from irrigated fields is attributed to their relatively higher productivity and planting index (PI) compared to other field types (Table 1).

Table 1. Area of rice fields, productivity, planting index, and harvested area based on the type of rice fields in Indonesia (Mulyani et al., 2022; Priyatno, 2022).

Type of rice field	Area of rice field	Percentage	Productivit	Planting index	Harvested area
	ha	%	t ha^{-1}		ha
Irrigated	4022955	46.04	5.22	1.47	5913744
Rainfed	2196	25.13	4.20	1.18	2590925
Dryland	1274	14.58	3.28	0.24	305760
Tidal swamp area	806469	9.23	3.99	1.25	1008086
Fresh water swamp	438825	5.02	4.01	1.13	495872
Total	8737948	100.00	-	-	10314387

Development of environmentally friendly rice

In recent decades, the frequency and intensity of climate change have increased significantly, reflecting ongoing environmental change and degradation—both intentional and unintentional—caused by human activities. These changes have led to a decline in the capacity of ecosystems to produce and sustain natural resources, reduced availability of those resources, and diminished quality of natural outputs. In the agricultural sector, such environmental disruptions present substantial challenges to food security and resilience (Amer et al., 2024).

One significant contributor to environmental degradation is the emission of CH_4 gas from rice cultivation in paddy fields. Agricultural practices such as soil and water management, fertilization, amelioration, and pest control are known to generate CH_4 emissions into the atmosphere. If these activities are carried out without sustainable practices over an extended period, they may not only degrade environmental quality but also lead to an increase in idle or abandoned land due to declining productivity. This situation poses a serious threat to the long-term sustainability of rice farming systems.

To minimize long-term losses, it is essential to reduce environmental degradation and the depletion of natural resource capacity caused by agricultural activities. One viable approach is the implementation of environmentally friendly farming practices. This strategy emphasizes the use of inputs and management techniques that lower CH_4 emissions while sustaining high rice productivity. From a crop management perspective, environmentally friendly rice cultivation involves the integration of several key components, including the selection of low-emission rice varieties, optimized crop management systems, appropriate planting methods, efficient cropping systems, and well-regulated plant spacing.

Environmentally friendly rice cultivation is guided by two core principles: Achieving high productivity and reducing CH_4 emissions. To support these goals, researchers have developed a range of sustainable farming systems, including Integrated Crop Management (ICM), super wide row planting, and Integrated Pest Management (IPM) (Despotović et al., 2019; Tang et al., 2025). By adopting an integrated approach that combines multiple technological components, it is possible to optimize rice yields, preserve soil and crop quality, and significantly lower CH_4 emissions, thereby contributing to more sustainable and climate-resilient rice farming systems.

The long-term intensive use of agricultural land without replenishing organic matter from crop residues has resulted in declining soil organic C levels. According to Tirtalistyani et al. (2022), approximately 65% of irrigated paddy fields in Indonesia have low organic matter content, defined as less than 2%. The absence of organic fertilization can lead to reduced rice productivity. In rice cultivation, the application of organic fertilizers plays a critical role by enhancing nutrient availability, stimulating soil microbial activity, improving the efficiency of nutrient uptake, increasing soil organic C levels, and ultimately boosting crop productivity. Moreover, organic fertilization has been shown to contribute to CH_4 emission reduction (He et al., 2023; Xing et al., 2025).

Farmers are increasingly familiar with environmentally friendly rice cultivation technologies, which incorporate a range of sustainable practices to enhance productivity while minimizing environmental impact. These technologies include several key components: (1) The selection of appropriate rice varieties based on land type and seasonal conditions, (2) proper seed selection, (3) optimal seedling age, (4) suitable planting systems and spacing, (5) regulation of the number of seedlings per planting hole, (6) balanced application of organic and inorganic fertilizers, and (7) implementation of IPM (Pandiangan et al., 2018).

CROP MANAGEMENT TECHNOLOGY

Land type and season

Rice productivity is influenced by the growing environment, including the location and timing of cultivation. Research by Yusuf et al. (2021) found that the Ciherang rice variety, when cultivated in tidal swamp areas, produces higher CH_4 emissions compared to cultivation in *lebak* wetlands and irrigated paddy fields. Among the three environments, 'Ciherang' cultivated in irrigated paddy fields resulted in the lowest CH_4 emissions.

Higher CH_4 emissions from rice cultivation in tidal swamp areas are primarily attributed to the dynamic oxidation-reduction conditions caused by the regular ebb and flow of water. This hydrological fluctuation accelerates the decomposition of organic matter, which serves as a key energy source for methanogenic bacteria (methanogens). As a result, the increased availability of organic substrates promotes microbial activity and enhances CH_4 production (Conrad, 2020). In contrast, *lebak* wetlands are characterized by more stagnant water conditions, leading to slower organic matter decomposition. This slower rate of decomposition contributes to the higher organic C content typically found in *lebak* soils compared to those in tidal swamp areas.

Among the three land types, rice cultivated in irrigated paddy fields exhibits more vigorous growth, as indicated by taller plants and a higher number of tillers. This enhanced growth leads to increased release of root exudates, which contain readily soluble C compounds such as sugars, amino acids, and organic acids. These compounds serve as substrates for microbial activity, including methanogens responsible for CH_4 production. However, the relatively better drainage conditions in irrigated paddy fields help suppress methanogenic activity while enhancing CH_4 oxidation. As a result, despite greater root exudation, CH_4 emissions from irrigated fields are generally lower due to more favorable redox conditions that promote CH_4 mitigation.

Ali et al. (2012) also reported significant differences in CH_4 emissions, productivity, and emission indices between rice cultivated in dryland areas and irrigated paddy fields. While CH_4 emissions and emission indices were higher in irrigated fields compared to dryland systems, rice productivity was also significantly greater (Table 2). The availability of adequate water in irrigated paddy fields supports more vigorous plant growth, which contributes to increased CH_4 emissions due to enhanced microbial activity and root exudation. However, this same condition also results in higher rice yields, highlighting a trade-off between productivity and environmental impact.

Table 2. Influence of land type on CH_4 emissions, productivity, and CH_4 emission index.

Source of data and land type	CH_4 emission	Productivity	Emission index
	kg CH_4 ha^{-1} $season^{-1}$	kg ha^{-1}	kg CH_4 kg^{-1} grain
Husny (2010)			
Irrigated	190.9	5748	0.033
Fresh water swamp	198.9	4626	0.043
Tidal swamp	399.3	4210	0.095
Ali et al. (2012)			
Irrigated	108.1	4927	0.022
Dryland	91.3	4561	0.020

Research on the influence of planting season on CH_4 emissions indicates that emission levels are generally lower during the dry season compared to the rainy season (Mboyerwa et al., 2022). On average, CH_4 emissions increase by approximately 40.63% during the rainy season. This rise is associated with greater water availability, which promotes more vigorous rice plant growth and, consequently, higher CH_4 emissions (Table 3). Enhanced plant growth results in increased production of root exudates—rich in soluble C compounds—which serve as substrates for methanogenic bacteria (Schwalm et al., 2024). Similar findings were reported by Nikolaisen et al. (2023), who observed that CH_4 emissions during the dry season were 35% lower than those recorded during the rainy season.

The ability of rice plants to emit CH_4 is also influenced by soil pH conditions (Mosharrof et al., 2021). During the rainy season, soil pH tends to increase due to improved water quality, creating more favorable conditions for methanogenic bacteria. Methanogens thrive in environments with a pH range of 6.0 to 8.0, with optimal

CH_4 production typically occurring around pH 7.0. These conditions are more likely to be met during the rainy season, which helps explain the higher CH_4 emissions observed during this period.

Table 3. Effect of planting season on CH_4 gas emissions in rice fields.

Source	CH_4 emission (kg CH_4 ha^{-1} $season^{-1}$)	
	Rainy season	Dry season
Panjaitan et al. (2015)	118.70	80.67
Sun et al. (2016)	389.00	291.00
Supriatin (2018)	79.00	66.87

Variety

The selection of suitable rice varieties is one of the most widely adopted crop management strategies by farmers to address suboptimal growing conditions and enhance rice productivity. Peatlands, despite their challenging characteristics, represent a potential resource for rice cultivation. Susilawati et al. (2019) recommended the use of 'Batanghari' and 'Banyuasin', two tidal rice varieties, for cultivation on peatlands due to their ability to produce low CH_4 emissions and lower CH_4 emission indices (Table 4).

Based on CH_4 emission index data, Wihardjaka et al. (2020) recommended the use of 'Inpari-13' for rice cultivation in irrigated fields. 'Inpari 13' exhibited lower methane emissions (32.8%) while maintaining a comparable yield performance to that of 'Ciherang' (Table 5). Similarly, research by Arisandi et al. (2018), conducted during the 2016 rainy season in irrigated fields, supports the cultivation of 'Inpari-13' due to their favorable balance between productivity and reduced CH_4 emissions.

Table 4. Methane emissions, productivity, and emission indices of several tidal rice varieties in peatland during the dry season of 2006 (Susilawati et al., 2019).

Variety	CH_4 emission	Productivity	Emission index
	kg ha^{-1} $season^{-1}$	kg ha^{-1}	kg CH_4 kg^{-1} grain
Batanghari	139.87	1800	0.078
Tenggulang	175.47	1900	0.092
Banyuasin	246.57	2800	0.088
Punggur	270.33	2800	0.097

Tabel 5. Methane emissions by rice varieties in irrigated rice fields in the 2018 rainy season (Wihardjaka et al., 2020).

Variety	CH_4 emission	Productivity	Emission index
	kg ha^{-1} $season^{-1}$	kg ha^{-1}	kg CH_4 kg^{-1} grain
Ciherang	122	4908	0.025
Inpari 13	82	4745	0.017
Inpari 18	164	4965	0.033
Inpari 19	96	3991	0.024
Inpari 20	114	4199	0.027
Inpari 23	155	4188	0.037
Inpari 24	78	4003	0.020
Inpari 29	122	4076	0.030
Inpari 30	130	3602	0.038
Inpari 31	178	4990	0.036
Inpari 32	171	5745	0.030
Inpari 33	150	4670	0.032

Variations in CH_4 emissions among different rice varieties cultivated in rainfed fields have also been documented by Mulyadi and Wihardjaka (2014), Wihardjaka and Sarwoto, (2015), Pramono et al. (2016), and Pramono et al. (2020). These studies offer alternative options for selecting rice varieties that produce low CH_4 emissions and emission indices. Based on these findings, several researchers have recommended specific varieties that are more environmentally sustainable, as summarized in Table 6. In line with these earlier studies, Wihardjaka et al. (2025) reported that amphibian rice cultivars such as 'Inpari 34', 'Inpari 39', and 'Inpari 42' emitted 2.2%-35.3% lower methane than 'Ciherang' under rainfed field conditions. Among these, 'Inpari 34' showed the lowest methane emissions. These findings confirm that certain rice varieties possess adaptive morphological and physiological traits—such as efficient aerenchyma formation and enhanced rhizosphere oxidation—that contribute to methane reduction without compromising grain yield performance, making them suitable for sustainable cultivation in rainfed ecosystems (Wihardjaka et al., 2025).

Table 6. Recommendations for suitable rice varieties to be cultivated in rainfed land during the dry season and rainy season.

Source of data	Reccommeded variety and season
Mulyadi and Wihardjaka (2014)	'Inpari-1' and 'Ciherang', rainy season 2012
Wihardjaka and Sarwoto (2015)	'Inpari-18' and 'Inpari-17', rainy season 2013
Pramono et al. (2016)	'Ciherang' and 'Inpari-30', rainy season 2016
Pramono et al. (2020)	'Inpari-32', dry season 2017

The release of CH_4 from soil to the atmosphere is strongly influenced by the physiological and morphological characteristics of rice plants. Research has shown that CH_4 emissions can increase up to 20-fold when rice is cultivated, compared to unplanted soil conditions. The CH_4 is released into the atmosphere through three primary mechanisms: aerenchyma transport, ebullition, and diffusion (Vroom et al., 2022). According to Arisandi et al. (2018), the potential for CH_4 emission is correlated with eight key plant traits: Plant height, number of tillers, stem aerenchyma area, panicle length, number of panicles, number of filled grains, 1000-grain weight, and overall productivity.

Rice plants possess aerenchyma tissues, specialized air spaces within their leaves, stems, and roots, that facilitate gas exchange between the plant and the surrounding paddy soil. As the plant matures, this gas exchange intensifies, leading to increased CH_4 production (Kim et al., 2018). Consequently, CH_4 emissions are closely influenced by the physiological characteristics of different rice varieties. The role of rice plants in CH_4 production is twofold: They act as conduits for CH_4 transport from the soil to the atmosphere via the aerenchyma network, and they contribute to the microbial processes of CH_4 production and oxidation by releasing root exudates and through the decomposition of senescent root tissues (Rajendran et al., 2024). These interactions highlight the critical influence of varietal traits on CH_4 dynamics in paddy ecosystems.

A key characteristic of rice varieties with low CH_4 emission potential is their shorter growth duration (Ardiarini et al., 2020). These varieties consistently exhibit shorter lifespans compared to commonly cultivated varieties in both rainfed and rainfed lowland ecosystems. The duration that rice plants remain in the field significantly influences total CH_4 emissions, as prolonged field presence increases the exposure time to anaerobic soil conditions conducive to CH_4 production.

The CH_4 emission potential in rice cultivation is also influenced by the plant's efficiency in utilizing photosynthetic products, as reflected in its productivity. Varieties that achieve comparable yields within a shorter growth duration tend to exhibit lower CH_4 emissions. Another important internal trait affecting CH_4 emission potential is the plant's root oxidation capacity, which plays a crucial role in regulating the redox status of the rhizosphere and suppressing CH_4 production under flooded conditions.

The formation and release of CH_4 from rice crops are significantly influenced by varietal differences, particularly in aerenchyma diameter and root exudation capacity (Qi et al., 2024). Root exudates provide essential C and energy sources for rhizospheric microorganisms, including methanogenic bacteria, thereby playing a critical role in the transformation and emission of CH_4. The rate and composition of root exudation are determined by both genetic and environmental factors, including rice variety, plant developmental stage, soil fertility, and the extent of root damage.

Plant biomass is another key characteristic that contributes to differences in CH_4 emission potential among rice varieties (Loaiza et al., 2024). A positive correlation has been observed between high biomass production and increased CH_4 emissions. Greater biomass results in a higher supply of carbohydrates derived from roots and root exudates, which serve as C sources. Under anaerobic or reducing soil conditions, these C compounds can be directly or indirectly utilized by methanogenic bacteria to produce CH_4 gas.

Crop management system

Crop management plays a crucial role in optimizing rice productivity while simultaneously minimizing CH_4 emissions and emission indices. Studies by Husny (2010) on tidal swamp lands and by Ramesh and Rathika (2020) on irrigated paddy fields demonstrated that rice cultivated using the System of Rice Intensification (SRI) generates significantly lower CH_4 emissions compared to conventional cultivation methods. The adoption of different crop management systems led to reductions in CH_4 emissions by 43.04% and 19.71%, respectively (Table 7).

Table 7. Influence of rice crop management systems on CH_4 emissions.

	CH_4 Emission based on crop management system (kg CH_4 ha^{-1} season^{-1})	
Source of data	System of rice intensification	Conventional
Husny (2010)	203.90	315.40
Ramesh and Rathika (2020)	213.22	255.25
Average	208.56	285.33

In addition to reducing CH_4 emissions, crop management using the SRI also enhances productivity and lowers CH_4 emission indices (Oo et al., 2018; Gangopadhyay et al., 2023). Improved plant growth, characterized by a greater number of productive tillers and enhanced photosynthetic efficiency, contributes to higher yields and reduced CH_4 emission indices (Table 8). Among the management systems evaluated, SRI demonstrated the lowest CH_4 emissions while achieving superior productivity compared to conventional practices. Considering both productivity and environmental impact, the adoption of SRI technology is strongly recommended.

The SRI offers several advantages over conventional rice cultivation methods. These benefits include: (a) Reduced seed requirements, (b) improved soil health, (c) decreased water usage and production costs, (d) lower CH_4 emissions, (e) suppression of weed growth, (f) enhanced grain quality, (g) increased farmer income, (h) reduction of disease vectors, and (i) improvements in tiller number, grain weight, and overall productivity (Thakur et al., 2014; 2023; Uphoff, 2023).

With regard to crop management using the ICM system, studies by Supriyo et al. (2020) in irrigated paddy fields during the 2016 dry season and Yulianingrum et al. (2019) in upland fields during the 2018 rainy season revealed notable differences in CH_4 emissions compared to conventional practices. In irrigated paddy fields, ICM technology reduced CH_4 emissions by 10.36 kg CH_4 ha^{-1} season^{-1}, while in upland fields, the reduction reached 44.00 kg CH_4 ha^{-1} season^{-1}. Additionally, ICM implementation improved rice productivity and decreased CH_4 emission indices (Table 9).

Compared to conventional crop management, the adoption of ICM in rice cultivation holds considerable promise due to several key advantages. These include: (1) Reduced water usage, (2) lower seed requirements, (3) decreased fertilizer inputs in both type and quantity, (4) potential for higher planting density (planting index), (5) increased productivity, (6) enhanced crop quality, and (7) reduced capital input requirements accompanied by higher profitability (Wihardjaka and Nursyamsi, 2012; Yulianingrum et al., 2019; Supriyo et al., 2020).

Table 8. Effect of crop management systems on productivity and CH_4 emission index of 'ADT 45' rice in irrigated paddy fields (Ramesh and Rathika, 2020).

Crop management system	Productivity	Emission index
	kg ha^{-1}	kg CH_4 kg^{-1} grain
System of rice intensification	5855	0.012
Conventional	5300	0.019

Table 9. Effect of rice crop management system on productivity and CH_4 emission index. ICM: Integrated crop management.

References	Productivity crop management system (kg ha^{-1})		Emission index of crop management system	
	Conventional	ICM	Conventional	ICM
Yulianingrum et al. (2019)	6140	6743	0.060	0.048
Supriyo et al. (2020)	3620	5063	0.021	0.011

Planting method

The planting method is a key cultivation technique that varies based on the treatment of rice seeds. When seeds are sown directly into the field, the method is referred to as direct seeding, whereas transplanting involves pre-treatment steps such as soaking, draining, and raising seedlings prior to planting. These differences influence both CH_4 emissions and rice productivity. According to Wihardjaka (2011; 2015), rice cultivated using the transplanting method results in higher CH_4 emissions and emission indices compared to the direct seeding method. Direct seeding has been shown to reduce CH_4 emissions by 23.71% (Table 10). This reduction is attributed to a shorter anaerobic phase in direct seeding, which delays the decline in redox potential following field flooding, thereby suppressing CH_4 production.

Findings from Wihardjaka (2011; 2015) indicate that 'Membramo' rice in upland areas and 'Ciherang' in rainfed areas, when cultivated using the direct seeding method, exhibit higher yields, lower CH_4 emissions, and reduced emission indices. Consequently, the direct seeding method is recommended for achieving both low CH_4 emissions and high rice productivity (Table 10). Several advantages of the direct seeding approach, as reported by Wihardjaka (2011; 2015) and Susilawati et al. (2019), include: (a) Labor efficiency, (b) shorter planting time, (c) suppression of weed growth, (d) reduced production costs, (e) lower CH_4 emissions and emission indices, (f) production of plumper rice grains, (g) higher planting indices, and (h) increased productivity.

Table 10. Effect of rice planting methods on CH_4 gas emissions, productivity and emission index.

Planting method and reference	CH_4 Emission	Productivity	Emission index
	kg CH_4 ha^{-1} season^{-1}	kg ha^{-1}	kg CH_4 kg^{-1} grain
Direct seedling			
Wihardjaka (2011)	74.63	4995	0.015
Wihardjaka (2015)	82.00	7263	0.011
Average	78.32	6129	0.013
Transplanting			
Wihardjaka (2011)	122.70	4157	0.030
Wihardjaka (2015)	82.56	4959	0.170
Average	102.63	4558	0.024

Planting sytem

Planting systems in rice cultivation are generally categorized into two types. The *Tegel* system features uniform spacing between rows and between individual plants, whereas the *Jajar Legowo* (*Jarwo*) system employs alternating row and plant spacing, with one row intentionally left empty (Figure 1). The potential of rice plants to emit CH_4 varies depending on the planting system used. According to Abduh et al. (2020), the commonly used *Tegel* system emits 185% more CH_4 compared to the *Jarwo* 2:1 system and results in approximately 30% lower productivity. Specifically, the *Jarwo* 2:1 system produces 2000 kg CH_4 ha^{-1} $season^{-1}$ with an emission index of 0.303 kg CH_4 kg^{-1} grain, while the *Tegel* system produces 5900 kg CH_4 ha^{-1} $season^{-1}$ with an emission index of 1.118 kg CH_4 kg^{-1} grain.

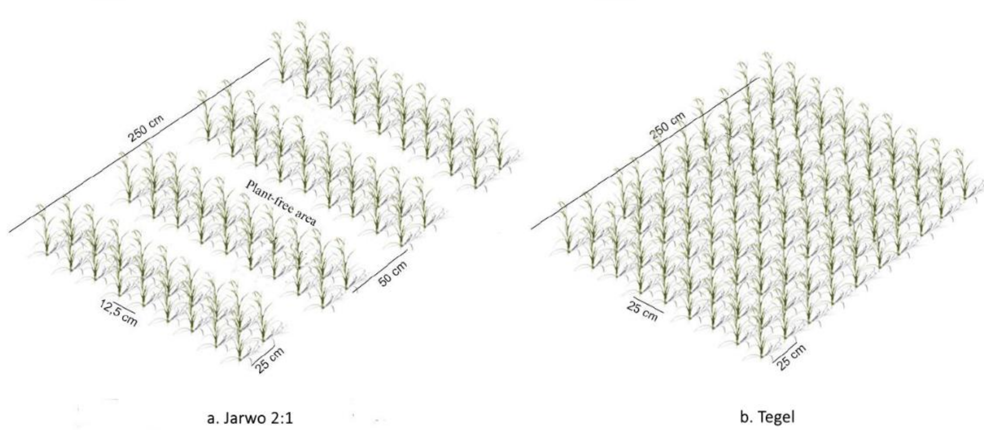

Figure 1. *Jarwo* 2:1 (a) and *Tegel* rice planting systems (b) (Abduh et al., 2020).

The lower CH_4 emissions observed in the *Jarwo* 2:1 planting system compared to the *Tegel* system are closely associated with differences in photosynthetic intensity and plant population density. The *Jarwo* 2:1 system supports a higher plant population, with approximately 213 333 tillers ha^{-1}, whereas the *Tegel* system supports only 160 000 tillers ha^{-1} (Masganti, 2021). Higher plant density in the *Jarwo* system reduces light penetration and photosynthetic activity in older leaves, increases interplant contact, and ultimately decreases the availability of root exudate substrates for methanogenic activity. Moreover, the delayed onset of soil reduction in this system is linked to the rice plant's capacity to transport atmospheric oxygen to the rhizosphere via aerenchyma tissue. This oxygen diffusion helps suppress anaerobic conditions favorable for CH_4 production—a mechanism that is distinct to rice and plays a critical role in mitigating CH_4 emissions (Xu and Zhang, 2022).

The lower CH_4 emissions observed in the *Jarwo* 2:1 planting system compared to the *Tegel* system are also attributed to the edge plant effect. According to Masganti (2021), in a 5 m × 5 m plot, the *Jarwo* 2:1 system contains 16 rows with 6 open spaces, resulting in a greater number of edge plants, while the *Tegel* system features only two edge rows without any empty spaces. The presence of these open areas allows for increased light penetration, enhancing photosynthetic efficiency and stimulating the activity of methanotrophic bacteria, which play a role in CH_4 oxidation (Abduh et al., 2020). Additionally, the *Jarwo* system lacks the continuous, direct planting pathways found in the *Tegel* system, further contributing to reduced CH_4 emissions.

Higher rice productivity associated with the *Jarwo* 2:1 planting method has also been documented by Susilastuti et al. (2018), Abduh et al. (2020), and Masganti (2021). Adopting the *Jarwo* 2:1 planting system has been shown to increase rice yield by 1743 kg ha^{-1}, or approximately 25.70%, compared to the *Tegel* system. The *Jarwo* 2:1 planting system also offers several advantages over the *Tegel* system. These include: (1) A higher plant population, more edge plants, and a greater number of productive tillers; (2) improved nutrient uptake and photosynthetic efficiency; (3) easier crop maintenance; (4) reduced rodent infestation and weed growth; and (5) increased productivity. Given these benefits, the *Jarwo* 2:1 planting system is recommended for future rice cultivation, as it effectively reduces CH_4 emissions and emission indices while sustaining high rice yields (Table 11).

Table 11. Influence of planting systems on rice productivity.

Source of data	Productivity based on planting system (kg grain ha^{-1})		Variety
	Tegel	*Jarwo* 2:1	
Darmawan (2016)	7650	12727	Inpari-7
Magfiroh et al. (2017)	6580	7280	Mekongga
Susilastuti et al. (2018)	9520	9840	Ciherang
Abduh et al. (2020)	5100	6600	Mentik Wangi
Masganti (2021)	5060	6180	Inpari-13
Average	6782	8525	-

Plant spacing

Plant spacing plays a critical role in determining plant population, which in turn affects CH_4 emissions and rice productivity. Generally, a denser plant population leads to increased CH_4 emissions but is inversely related to rice yield. This observation is consistent with the findings of Sutrisna et al. (2018), who reported that closer plant spacing (12.5 cm) results in a higher plant population than wider spacing (15.0 cm). Increased plant density intensifies root metabolic activity and facilitates greater CH_4 release into the atmosphere. Specifically, a 12.5 cm spacing produced 6742 kg CH_4 ha^{-1} $season^{-1}$ with an emission index of 1.018 kg CH_4 kg^{-1} grain, whereas a 15.0 cm spacing yielded lower emissions of 5182 kg CH_4 ha^{-1} $season^{-1}$ with an emission index of 0.852 kg CH_4 kg^{-1} grain (Table 12).

The findings of Sutrisna et al. (2018) further demonstrate that CH_4 emissions, rice productivity, and emission indices are influenced by the width of the empty space between planting rows. A narrower spacing of 40 cm results in lower CH_4 emissions and emission indices, while enhancing productivity, compared to a wider spacing of 50 cm. Specifically, rice cultivated using the *Jarwo* 2:1 system with a 40 cm spacing generated an average CH_4 emission of 5325 kg ha^{-1} $season^{-1}$, a productivity of 6450 kg ha^{-1}, and an emission index of 0.820 kg CH_4 kg^{-1} grain. In contrast, a wider 50 cm spacing resulted in higher CH_4 emissions of 6549 kg CH_4 ha^{-1} $season^{-1}$, slightly lower productivity at 6255 kg ha^{-1}, and a higher emission index of 1.046 kg CH_4 kg^{-1} grain.

Plant spacing is a key crop management technique used to regulate plant population and optimize productivity. According to Chadhar et al. (2020), field experiments conducted in 2010 and 2011 using 'Super Basmati' under the SRI demonstrated that the highest productivity in the *Tegel* system (4.35 t ha^{-1}) was achieved with a spacing of 25 × 25 cm. In comparison, narrower (20 × 20 cm) and wider (30 × 30 cm) spacings resulted in lower yields of 3.65 and 3.94 t ha^{-1}, respectively. Optimal plant spacing improves photosynthetic efficiency by preventing leaf overlap in densely populated plots, enhances nutrient uptake efficiency, and maximizes yield components.

Table 12. Effect of planting distance on CH_4 gas emissions, productivity and emission index of 'Inpari-30' rice on irrigated rice field in the 2016 rainy season (Sutrisna et al., 2018).

Plant spacing of *Jarwo*	CH_4 Emission	Productivity	Emission index
	kg CH_4 ha^{-1} $season^{-1}$	kg ha^{-1}	kg CH_4 kg^{-1} grain
25 × 15 × 40 cm	4403	6040	0.729
25 × 15 × 50 cm	5860	6120	0.958
Average	5182	6080	0.852
25 × 12.5 × 40 cm	6247	6860	0.911
25 × 12.5 × 50 cm	7237	6390	1.133
Average	6742	6625	1.018

CONCLUSIONS

Indonesia's rice production capacity must continue to be strengthened to meet national food demand and support global food security. This can be achieved through the sustainable utilization of various land types, including irrigated fields, rainfed fields, drylands, tidal swamps, and freshwater swamps. The development of rice cultivation in Indonesia should not focus solely on achieving high productivity, but must also account for environmental sustainability and food security concerns. The CH_4 emissions vary significantly across land types, with the highest emissions observed in tidal swamp areas, followed by marshy and irrigated fields. Seasonal variations also influence emissions, with the rainy season generally producing more CH_4 than the dry season. To reduce CH_4 emissions while maintaining or enhancing rice productivity, effective plant management practices are essential. These include the selection of appropriate rice varieties, optimized crop management systems, planting methods, planting systems, and plant spacing. Recommended crop management technologies include the use of 'Banyu Asin' and 'Punggur' rice for tidal swamp areas; 'Ciherang' and 'Mentik Susu' for irrigated fields; and 'Ciherang' along with 'Inpari 1', 'Inpari 17', 'Inpari 18', 'Inpari 30', and 'Inpari 32' for rainfed areas. Best practice management systems involve the adoption of the System of Rice Intensification or Integrated Crop Management, using the direct seeding method and the *Jajar Legowo 2:1* planting system. The recommended plant spacing configurations include 25 × 15 × 40 or 25 × 12.5 × 40 cm to optimize growth while minimizing CH_4 emissions.

Author contribution

Conceptualization: A.M.A., M.M., N.N.S. Data curation: A.M.A., M.M., K.A., A.H., R.Y., P.H.S., E.M., A.F., N.N., E.E., Y.R.D. Writing-original draft: A.M.A, M.M., N.N.S., I.K., A.F., K.A., A.H., R.Y., P.H.S., E.M., A.F., B.A.B., N.N., E.E., Y.R.D. Writing-review & editing: A.M.A., M.M., N.N.S. All co-authors reviewed the final version and approved the manuscript before submission.

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