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Potential for CO₂ emission reduction from large-scale rice fields in the Mekong Delta, Vietnam: a case study on OM4040 rice variety

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Transitioning from traditional smallholder to large-scale, mechanized rice farming offers significant potential for reducing greenhouse gas (GHG) emissions in Southeast Asia. This study assessed the environmental and economic performance of large-scale OM4040 rice cultivation in the Mekong Delta, Vietnam, using IPCC methodologies. Results showed a 15.5% reduction in CO₂-equivalent (CO₂e) emissions per ton of rice produced, driven by improved water management (e.g., alternate wetting and drying), laser-assisted land leveling, and optimized fertilizer use. Mechanized operations were found to increase fuel-based emissions, but higher yields offset this effect. Additionally, postharvest straw reuse contributed to avoiding 2.4–3.0 tons CO₂e per 10 ha per season, reinforcing circular economy principles. Economically, large-scale systems were more profitable only when land rental costs were excluded. The integration of carbon efficiency and sustainability indices provided a comprehensive evaluation of emission trade-offs. These findings support the adoption of climate-smart rice production systems and underscore the need for enabling infrastructure and land policy reforms to enhance scalability and sustainability.

KEYWORDS

CO₂ decrease, large fields, Mekong Delta, sustainable agriculture, food

1 Introduction

The Mekong Delta, located in southwest Vietnam, covers an area of 40,921.7 km². The Mekong Delta accounts for 12.35% of Vietnam's total land area and is home to a population of 17.46 million ([Vietnam National Statistics Office, 2023](#)). In Vietnam, traditional rice farming is typically carried out by families on small land plots ([Phong et al., 2023](#)). In contrast, large-scale rice production employs mechanized and technologically advanced methods to cultivate rice over extensive areas to produce a large amount of rice for export. Chemical fertilizers and pesticides are applied systematically to enhance yields and control pests ([Meng et al., 2024](#)). Implementing improved water management techniques can reduce methane emissions by up to 48% of methane while conserving water ([Arai, 2022; Ji et al., 2024](#)).

Paddy rice planting has long been the backbone of food security in many parts of the world, particularly in Asia, yet it now finds itself both threatened by and contributing to climate change. Rising temperatures, erratic rainfall, and increased extreme weather events challenge traditional flooded cultivation methods that have sustained rice production for centuries ([Huang et al., 2020](#)). In response, researchers and farmers are adopting climate-smart

practices—such as alternate wetting and drying techniques and improved, resilient rice varieties—to reduce greenhouse gas emissions and enhance water-use efficiency while safeguarding productivity. This integrated approach aims to mitigate the environmental footprint of rice farming and ensure the sustainability and resilience of this critical agricultural system in a rapidly changing climate (Dong et al., 2023). Paddy rice cultivation is a fundamental practice for global food security. Global GHG emissions are ~7,870 kg, with 94% of CH₄ (Qian et al., 2023). In response to climate change and environmental degradation, there is an urgent need to transition toward sustainable rice farming practices that maintain high productivity while minimizing emissions. Among these approaches, large-scale, mechanized rice farming has emerged as a promising model. Techniques such as Alternate Wetting and Drying (AWD) and laser leveling are increasingly adopted to improve efficiency and reduce emissions (Tang et al., 2023). Effective water management in paddy rice cultivation is crucial for reducing greenhouse gas emissions, particularly methane produced under the anaerobic conditions of continuously flooded fields. Adopting suitable water management practices can lead to more sustainable rice production by reducing greenhouse gas emissions, conserving water resources, and maintaining or even improving crop yields (Phungern et al., 2023).

Fertilizer use in agriculture contributes to N₂O emissions through several channels. N₂O emissions were 1.67, 1.47, and 1.29 kgN₂O/ha for urea-nBTPT, P, and NPK IBDU use, respectively (Phong et al., 2017). Nitrogen fertilizer contributes about 5% of global greenhouse gas emissions (Gao and Serrenho, 2023). The amount of nitrogen fertilizer used affected greenhouse gas emissions (Primitiva et al., 2022)—farmers to promote sustainable agricultural practices and mitigate the environmental impact of fertilizer use (Walling and Vaneekhaute, 2020). Applying nitrogen fertilizers more efficiently can minimize N₂O emissions associated with rice cultivation (Hashim et al., 2024).

The recent studies provided comprehensive insights into the sustainable management of agricultural and food waste within the framework of the circular economy (Singh et al., 2022; Dey et al., 2024). A study focused on various waste management techniques such as composting, biogas production, and resource recovery through advanced technologies, highlighting global challenges and opportunities in agricultural waste valorization (Singh et al., 2022). Another study examined the scale of food waste generation and its industrial utilization, emphasizing processes that transform waste into valuable products like biofuels and biopolymers (Dey et al., 2024). Both sources underscore the importance of integrating waste recovery strategies into policy and practice to promote environmental sustainability and reduce the ecological footprint of agri-food systems. Together, they offer a holistic view of how organic waste streams can be transformed from environmental burdens into economic and ecological assets.

Additionally, sustainable rice systems should incorporate effective waste management strategies, particularly in managing agricultural and food waste. Food waste in post-harvest and processing phases can contribute to substantial greenhouse gas emissions if not properly handled. Integrating waste-to-value approaches such as composting straw and husks, converting food waste into biogas, or producing biochar, can enhance circularity and resource efficiency. These practices not only reduce emissions but also improve soil health and offer new economic opportunities for farming communities (Singh et al., 2022; Dey et al., 2024).

This study focuses on the OM4040 rice variety, a high-yield, short-duration cultivar well-suited to mechanized systems. The main purpose of this study is to evaluate the potential for reducing CO₂-equivalent (CO₂e) emissions through the adoption of large-scale, mechanized rice production, while also assessing the associated economic impacts and waste management benefits. By comparing traditional and mechanized systems in Can Tho, Vietnam, we aim to quantify emission reductions and explore how climate-smart practices such as alternate wetting and drying (AWD), laser-assisted land leveling, and postharvest straw reuse, contribute to sustainable agriculture in the Mekong Delta.

2 Research method

2.1 Experimental design

Field experiments were conducted in Co Do District, Can Tho City (2021–2023) (Figure 1). Traditional plots (0.3–0.6 ha) represented smallholder practices, while a 10-ha mechanized field represented large-scale operations. Both used OM4040 rice. Key parameters (inputs, yields, emissions) were monitored through sowing, growth, and harvest stages. The traditional model design reflects a simplified representation of smallholder rice farming. The selection of small plots without access to land leveling, mechanization, or coordinated infrastructure did not fully capture the range of traditional practices evolving in the Mekong Delta, especially among cooperative or semi-commercial smallholders. However, the chosen design allowed for a controlled comparison between a basic smallholder system and a fully mechanized model. While this setup highlights clear contrasts, we acknowledged that it introduced structural asymmetries which may influence the degree of observed differences.

2.2 Data collection and validation

Primary data was collected through field logs and structured interviews with smallholders. Secondary data was obtained from BeeViet Company Ltd. for large-scale operations. Data were normalized to per-hectare units and validated using two-step checks for outliers and consistency.

2.3 Emission calculation

Mechanized fuel use (plowing, sowing, harvesting): 40–60 L/ha-crop × 2.68 kg CO₂e/L.

The mass of CH₄ was estimated by Eq. 1.

$$mCH_4 \text{ (kg - CH}_4 \text{ / ha)} = D \text{ (days)} \times EF_{CH_4} \text{ (kg - CH}_4 \text{ / ha.day)} \quad (1)$$

D is PR farming days (90 days of OM4040); EF_{CH₄} is 2.78 kg-CH₄/ha.day (Liem et al., 2022).

The mass of N₂O was estimated by Eq. 2.

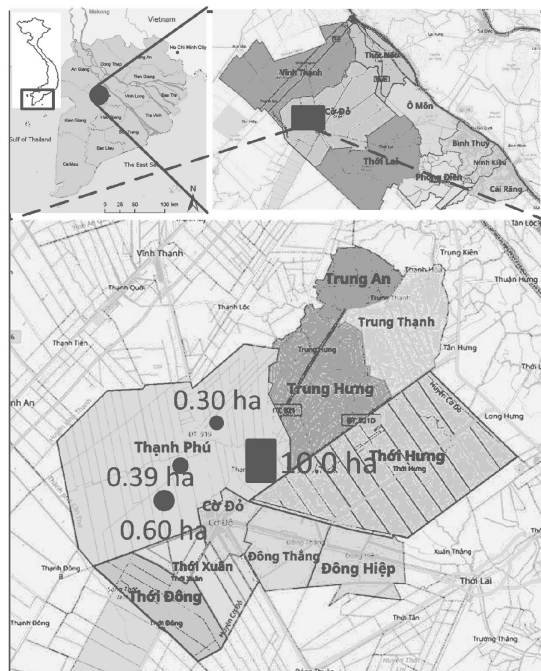


FIGURE 1
Research locations in Co Do District, Can Tho city.

$$m_{N_2O} (kg - N_2O / ha) = mN - CF (kg - N - CF / ha) \times EF_z (kg - N_2O - Nkg - N - CF^{-1}) \times 1.57 \quad (2)$$

In which,

$mN - CF$ is the amount of $N - CF$ applied; EF_z is the emission factor applied for farming system type [1% $N_2O - N$ for the upland crop (IPCC, 2006) and 0.59 (0.3% $kg - N$, IPCC) – 0.768 $kg - N_2O/ha$ season-1 for PR farming (Vo et al., 2017); 1.57 is the value of 44/28 – the mass of N_2O and N].

GHG emission and fertilizer element gains (Em-FG) index calculation. The Em-FG index was recommended to clearly explain the relationship between how much emission trade-off and fertilizer elements are applied for one hectare of growing area to produce one tonnage of the main product (Liem et al., 2022). The Em-FG of growing area: $Em-FG (kg-CO_2e / kg-elements.ha) = GHGs \text{ emission } (kg-CO_2e/ha) / [nitrogen \text{ element } (kg-N/ha) + phosphate \text{ element } (kg-P_2O_5/ha) + potassium \text{ element } (kg-K_2O/ha)]$. The Em-FG of grain: $Em-FG (kg-CO_2e/kg-elements.t) = GHGs-FG (kg-CO_2e/kg-nutrients.ha) / Productivity (t/ha)$.

Straw burning emissions avoided: 2.4–3.0 tons $CO_2e/10 \text{ ha}$.

2.4 Carbon metrics

This study used emission and conversion factors specific to Vietnam, which is the most accurate approach for estimating GHG emissions, referencing the default emissions from IPCC (2006). A 100-year time horizon was used to set the system boundaries, and all emissions were converted to CO_2e -equivalents. This study included emission estimates from mechanized farming activities such as plowing, leveling, direct

seeding, spraying, and harvesting. Fuel consumption was estimated based on standard diesel usage rates for rice farming in the Mekong Delta, ranging from 40 to 60 liters per hectare per crop. These values were multiplied by the IPCC emission factor of 2.68 $kg - CO_2e/liter$ to calculate mechanization-related emissions (IPCC, 2013). In evaluating the benefits of laser land leveling, literature-based methane reduction estimates ranging from 10 to 15% were incorporated to reflect improved irrigation efficiency and reduced anaerobic zones. These mitigation values were cross-validated with the field conditions in Can Tho.

The mass of by-products was estimated using the crop-to-residue ratio (CRR). This study qualified straw and rice through its dry grain. The CRR is as follows $CRR_{Rice \text{ straw}} = 1.53$ (Purohit, 2009). Carbon emissions and removals were estimated by Eq. 3.

$$C_{Net} (kg - C / ha) = C_O (kg - C / ha) - C_I (kg - C / ha) \quad (3)$$

In which:

C_I is total carbon inputs ($kg - C/ha$) based on CO_2e emission and was determined by $C_I = CO_2e \text{ emission} \times 0.27$ (12/44 as the mass of C and CO_2); C_O is total carbon outputs ($kg - C/ha$; including product and by-products) and was determined $C_O = \sum (Y_j \times \%C_j)$ (Y_j : yield of plant j part – grain, stalk/straw, and shell in $kg - C/ha$; $\%C$: carbon content of plant j part in which grain is about 45.2% and straw is about 53.5% (Liem et al., 2024).

GHG emissions from inputs were estimated using Eq. 4.

$$GHGs_{input} = \sum [m_k (kg - input_k / ha) \times EF_k (kg - CO_2e kg - input_k^{-1})] \quad (4)$$

$GHGs \text{ emission from manage soil} = \sum [m_q (kg - gas_q/ha) \times ConF_q (kg-CO_2e kg - gas_q^{-1})]$; m_k is the mass of input k ; EF_k is the emission factor of inputs k production and application; m_q is the mass of soil emission from gas q (CH_4 and N_2O); $ConF_q$ is the conversion factor of gas q to CO_2e (1 $kg - N_2O = 265 kg - CO_2e$ and 1 $kg - CH_4 = 28 kg - CO_2e$) (IPCC, 2013).

$$\text{Carbon efficiency : } CE = CO (kg - C / ha) / CI (kg - C / ha) \quad (5)$$

Carbon sustainability index (CSI) = $[C_O (kg - C/ha) - C_I (kg - C/ha)] / CI (kg - C/ha)$.

$$Nu_{j-g} (kcal / ha) = m_{j-g} (t / ha) \times NuC_{j-g} (kcal / t) \quad (6)$$

m_{j-g} is the mass of crop j grain (t/ha); NuC_{j-g} is the nutrient conversion of crop j grain ($kcal/t$). In the case of Vietnam paddy rice, rice was about 80.4% rice grain (Liem et al., 2024). Emission trade-offs for nutrient gains ($g - CO_2e/kcal$) = Emission for 1 tonnage of product ($g - CO_2e/t$)/Nutrient in one tonnage of grain ($kcal/t$).

2.5 Economic analysis

For the economic evaluation, two distinct scenarios were considered: (1) Scenario A with land rental: assumes a rental fee of 14 million VND/

ha/year applied to the large-scale model, (2) scenario B without land rental: reflects owner-operated systems where land cost is excluded. This dual-scenario framework allowed for a more realistic comparison of economic viability under varying land tenure arrangements. Costs, revenues, and profits were compared across both scenarios.

3 Results and discussion

3.1 Productivity and input use

OM4040 variety significantly improved input efficiency and yield compared to traditional smallholder systems. The large-scale system achieved a slightly higher average yield of 7.8 tons/ha, compared to 7.3 tons/ha in traditional systems, while using about 32% less seed (85.0 kg/ha vs. 125.6 kg/ha) as showed in Table 1. This enhanced performance is attributed to precision farming practices like laser-assisted land leveling, direct seeding, and mechanized harvesting, which led to more uniform planting and fewer losses.

The large-scale and mechanized systems showed improved input efficiency and reduced pesticide usage by 50%, primarily due to coordinated pest management and stricter quality control, especially for rice destined for export. Consequently, total production expenses were reduced from approximately 28 million VND/ha in traditional systems to 36 million VND/ha in the large-scale model. The cost of the large-scale model included a land rent of 14 million VND/ha/year. Thus, the total production expenses amounted to 22 million VND/ha for the large-scale model if the company owned the land. This study demonstrated that mechanized, large-scale farming can enhance productivity and reduce input costs, offering a more economically and environmentally viable alternative.

An interesting finding was the optimization of fertilizer and pesticide use in the large-scale model. Nitrogen application was slightly lower (180.0 kg/ha vs. 200.2 kg/ha), and pesticide costs were halved due to integrated pest management practices. This aligns with studies showing how smart farming reduces reliance on agrochemicals

which aligns with findings on smart farming's role in reducing agrochemical dependence (Hashim et al., 2024).

Despite higher overall expenses driven by mechanization and land rental (36.5 million VND/ha), the large-scale model proved more profitable when land rental costs were excluded. This suggests that favorable land tenure arrangements are a key factor in the economic viability of this type of farming. This aligns with previous studies highlighting cost-efficiency and yield gains from mechanized systems (Gao and Serrenho, 2023).

3.2 GHG emissions

Table 2 summarizes the GHG emissions per hectare for both traditional and large-scale systems. Methane (CH₄) from flooded fields was the dominant source, with 7,900 kg CO₂e/ha in traditional plots and 6,950 kg CO₂e/ha in large-scale plots. Alternate Wetting and Drying (AWD) and improved irrigation control from laser land leveling, which resulted in a 12% reduction in CH₄ emissions from flooded fields (6,950 kg CO₂e/ha vs. 7,900 kg CO₂e/ha). This finding is supported by other research confirming AWD's effectiveness in reducing CH₄ emissions by as much as 48% without compromising yield (Arai, 2022; Ji et al., 2024).

Nitrous oxide (N₂O) emissions were also lower in the large-scale systems (250 kg CO₂e/ha vs. 320 kg CO₂e/ha), which were likely due to more efficient fertilizer application and reduced nitrogen loss. While mechanized operations did slightly increase fuel-based emissions, higher yields more than compensated for this increase (Primitiva et al., 2022). Fuel emissions from mechanized land preparation were slightly higher (1,321.6 vs. 1,300.4 kg CO₂e/ha). The study showed a notable reduction in GHG emissions per ton of rice produced in the large-scale system. The carbon efficiency improved by 15.5%, with emissions of 1,135 kg CO₂e per ton of rice, compared to 1,356 kg CO₂e per ton in traditional systems.

In addition to these technological advancements, incorporating comprehensive waste management strategies into rice farming operations further strengthens sustainability. Utilizing crop residues like straw and husks through composting or energy recovery methods

TABLE 1 Rice farming profit and cost in Winter–Spring rice season 2021–2022 and 2022–2023.

No	Cultivation	Large-scale Field Aver/ha	Traditional cultivation			
			Farmer 1	Farmer 2	Farmer 3	Aver/ha
1	Area, ha	10	0,4	0,6	0,3	0.43
2	Quantity of rice variety, kg	85.0 ± 7.1	49,5	70,0	42,5	125,6 ± 13.2
3	Total cost, M. VND	36.5 ± 5.3	10.9 ± 1.4	17.1 ± 1.8	8.7 ± 0.7	28.5 ± 3.0
	In which, Fertilizes					
	N, kg/ha	180.0 ± 7.1	192,3 ± 18.1	208,3 ± 11.8	200.0 ± 47.1	200,2 ± 13.6
	P, kg/ha	200.0 ± 14.1	224,4 ± 27.2	225,0 ± 11.8	233,3 ± 0.0	227,6 ± 13.0
	K, kg/ha	90.0 ± 7.1	89,7 ± 18.1	108,3 ± 11.8	116,7 ± 23.6	104,9 ± 5.7
	Pesticides, M. VND/ha	1.2 ± 0.0	1.4 ± 0.2	1.4 ± 0.1	1.4 ± 0.1	1.4 ± 0.1
4	Total cost, M. VND	36.5 ± 5.3	10.9 ± 1.4	17.1 ± 1.8	8.7 ± 0.7	28.5 ± 3.0
5	Yield, tons	7,8 ± 0.4	3,05 ± 0.1	4,2 ± 0.3	2,2 ± 0.1	7,3 ± 0.3
6	Revenue, M. VND	55.7 ± 3.9	21.0 ± 0.9	30.1 ± 0.9	15.2 ± 0.7	51.4 ± 0.5
7	Profit, M. VND	19.2 ± 1.4	10.1 ± 2.3	13.1 ± 0.8	6.5 ± 0.1	22.9 ± 2.5

TABLE 2 CO₂e emission from paddy rice cultivation.

Source Of Emissions	Large-scale field (kg CO ₂ e/ha)	Traditional field (kg CO ₂ e/ha)
CH ₄ from flooded fields	6,950.0	7,900.0
N ₂ O from nitrogen fertilizer	250.0	320.0
CO ₂ e from phosphorus fertilizer	280.0	318.6
CO ₂ e from potassium fertilizer	49.5	57.7
CO ₂ e from land preparation/fuel use	1,321.6	1,300.4
Total CO ₂ e emissions	8,851.1	9,896.7
Yield (tons/ha)	7.8	7.3
CO ₂ e per ton of rice (kg/ton)	1,135.0	1,355.6

(e.g., anaerobic digestion for biogas production) significantly reduces the environmental burden of agricultural waste. Moreover, addressing food waste across the supply chain, from postharvest losses to retail and household levels, can help close the loop in rice production. These practices align with circular economy principles and support climate-smart agriculture by minimizing waste, enhancing resource use efficiency, and reducing overall CO₂ emissions (Singh et al., 2022; Dey et al., 2024).

This study demonstrated that large-scale rice farming can reduce CO₂e emissions per ton of rice produced, the current analysis did not fully account for emissions arising from mechanized operations. Mechanized land preparation, sowing, pesticide application, and harvesting, all integral to large-scale systems require the use of fuel-powered machinery, contributing additional CO₂ emissions. Using conservative estimates, diesel consumption for tractor operations can range from 40 to 60 L/ha.crop, which equated to approximately 107–161 kg CO₂e/ha per crop season, based on the IPCC diesel emission factor of 2.68 kg CO₂e per liter. Incorporating this figure would slightly raise total emissions in large-scale systems, although the per-ton CO₂e remains lower due to higher yields. Moreover, one of the key mitigation measures - laser-assisted land leveling has been shown in previous research to reduce methane emissions by 10–15% through improved water control, fewer anaerobic zones, and optimized irrigation schedules.

CE and CSI provided a more detailed picture of the trade-offs involved in intensifying agricultural practices. As emphasized metrics which are vital for evaluating the trade-offs inherent in agricultural intensification (Equations 5, 6; Qian et al., 2023).

3.3 Economic comparison

The economic comparison between traditional and large-scale rice systems in this study includes an arbitrary deduction of 14.0 million VND/ha to represent land rental costs, assuming a scenario where land is company-owned. However, this assumption significantly affects profit margins and may misrepresent the cost-effectiveness of large-scale farming for broader replication. To address this, we present two economic scenarios: including land rental and excluding land rental.

With rental costs factored in, net profit from large-scale production drops from 19.2 to approximately 5.2 million VND/ha less than the average profit achieved by smallholder farmers (7.6 million VND/ha). Excluding rental costs, the large-scale model outperforms traditional methods. This highlights the importance of land tenure arrangements in determining the profitability of scalable rice farming. A more rigorous cost-benefit analysis over multiple seasons, incorporating fixed capital costs, depreciation of machinery, and long-term operational efficiencies, is recommended to accurately reflect economic sustainability.

This approach aligns with the circular economy model, which emphasizes converting agricultural residues into valuable resources. Beyond reducing emissions, straw reuse provides an additional source of revenue for farmers, with sales reaching up to 2.5 million VND/ha in local markets. The integration of waste-to-value strategies, such as composting, biogas production, and biochar creation, can significantly enhance a farm's sustainability and offer new economic opportunities.

3.4 Waste management and circular economy

Effective post-harvest waste management in large-scale farms contributed to further emission reductions. Unlike traditional smallholders who often burn straw due to logistical and labor challenges, large-scale farms use combine harvesters and balers to collect straw efficiently. This practice prevents open-field burning, which in this study avoided 2.4–3.0 tons of CO₂e emissions per 10 hectares per season. This approach supports findings in earlier studies which emphasized the role of circular economy practices in reducing agricultural emissions while creating economic value from waste (Singh et al., 2022; Dey et al., 2024).

In traditional rice farming systems, which are typically small-scale, postharvest straw collection is often constrained by limited access to transportation infrastructure. As a result, the revenue generated from selling straws was relatively low and frequently did not offset the labor costs associated with manual collection. Consequently, many farmers incorporated the straw into their fields by plowing it under, often combined with microbial agents such as *Trichoderma* to accelerate decomposition. On smaller or less accessible plots, open-field straw burning remained common, contributing to haze and localized air pollution. Improved postharvest residue management in large-scale systems further reinforces their environmental advantages, especially when avoiding straw burning, as detailed earlier (Singh et al., 2022).

Moreover, improved infrastructure in mechanized farms allows for greater collection efficiency, enabling the transformation of straw into compost or energy, which supports both climate goals and rural livelihoods. This aspect of resource circularity is a key pillar of climate-smart agriculture and must be considered in future policy frameworks.

3.5 Limitations

While this study provided strong evidence for the environmental and economic benefits of large-scale rice farming, it did have some limitations. The design, which compared small, traditional plots to a large mechanized field, created structural differences that influenced the results. For instance, the small plots were unable to use key practices like laser-assisted land leveling, which is a major factor in reducing methane

emissions. The findings emphasize that the observed benefits were not solely from the OM4040 rice variety itself, but from the integrated system-level changes in management, technology, and waste handling that are enabled by larger scale farming. Future research should explore long-term carbon budgeting over multiple seasons and assess the scalability of these systems under different land ownership models.

4 Conclusion

This study provided new empirical evidence on the environmental and economic advantages of transitioning from traditional smallholder rice farming to large-scale, mechanized systems in the Mekong Delta, using the OM4040 rice variety. A key contribution was quantifying CO₂-equivalent emissions across both models and linking emission reductions to specific interventions such as laser-assisted land leveling, optimized fertilizer use, and improved postharvest waste management. The research highlights that emission intensity (CO₂e per ton of rice) was reduced by 15.5%, even when accounting for emissions from mechanized operations.

Importantly, this was among the first studies in Vietnam to integrate carbon efficiency metrics (CE and CSI) into the evaluation of rice production systems, providing a more nuanced picture of the carbon trade-offs associated with intensification. The reuse of straw - avoiding open-field burning also contributed up to 3.0 tons CO₂e reduction per 10 hectares per season, illustrating a tangible climate benefit of circular waste management strategies.

While OM4040 played a role in yield stability, the observed gains were primarily driven by system-level changes in land use, water control, and residue handling. These findings underscore that emission reductions were not inherent to the rice variety alone but stem from integrated farm management approaches enabled by scale and technology.

Future research should explore long-term carbon budgeting across multiple cropping cycles, assess the scalability of mechanized systems under different land tenure arrangements, and evaluate socio-economic trade-offs across diverse rice-producing regions in Vietnam. Moreover, integrating digital technologies for real-time emissions tracking and strengthening farmer cooperatives for shared mechanization access may be crucial next steps to advance climate-smart rice production. As climate pressures mount, such interventions will be central to achieving national and global targets for low-emission, sustainable agriculture.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

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Author contributions

TP: Data curation, Software, Visualization, Formal analysis, Writing – original draft, Resources, Conceptualization, Project administration, Methodology, Validation, Investigation, Writing – review & editing. MC: Methodology, Writing – review & editing, Conceptualization, Visualization, Formal analysis.

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Conflict of interest

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