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Carbon footprint research and mitigation strategies for rice-cropping systems in China: a review

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Reducing greenhouse gas (GHG) emissions and quantifying the carbon footprint (CF) of rice-cropping systems in the context of food security is an important step toward the sustainability of rice production. Exploring the key factors affecting emission reduction in rice production is important to properly evaluate the impact of China's rice-cropping systems on global climate change. This review provides an overview of the direct and indirect CF in rice-cropping systems; analyzes the influencing factors in terms of rice-based cropping systems, varieties and agronomic practices; and proposes mitigation strategies. Different studies have shown that direct and indirect GHG emissions in rice-based cropping systems accounted for 38.3 to 95.5% and 4.5 to 61.7% of total emissions, respectively. And the CFs of ratoon rice, rice–wheat, rice–maize, rice–rapeseed, and rice–fish systems ranged from 316,9 kg CO_2-eq kg^{-1} to 258,47 kg CO_2-eq kg^{-1}, which are lower than that in a double-rice planting system. High-yielding rice, drought-resistant rice, and other hybrids can mitigate GHG emissions from paddy fields by 3.7 ~ 21.5%. Furthermore, organic matter, water, tillage, straw incorporation, conservation tillage, reduced nitrogen fertilizer use, and added biochar and methane inhibitors could reduce emissions. Therefore, through reasonable agronomic measures, variety selection and optimal layout of rice-based rotation systems, the carbon neutral rate of rice production can be improved to help the national carbon sequestration and emission reduction target.

KEYWORDS

rice-cropping system, carbon footprint, greenhouse gas emissions, emission reduction, China

1 Introduction

A series of ecological and environmental problems caused by global warming have become a major challenge that humans must confront (Fu et al., 2015). Global warming is caused by the increased concentration of greenhouse gases (GHGs) in the atmosphere and leads to a phenomenon widely known as the "greenhouse effect," which directly leads to extreme weather such as droughts, floods, typhoons, and catastrophic precipitation (Hussain et al., 2015). The average surface temperatures will rise by 2.2°C to 3.5°C by the middle of the century if the rate of global warming is not controlled [IPCC (Intergovernmental Panel on Climate Change), 2023]. Climate change is seriously affecting agricultural production. The significant increase in temperatures has seriously contributed to the increased frequency of crop disasters and reduced yields. The three major GHGs that contribute to global climate change are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). World food security and even human survival will face serious challenges if effective measures are not taken to achieve net zero GHG emissions [IPCC (Intergovernmental Panel on Climate Change), 2021]. Therefore, carbon sequestration and emission reduction are widely focused on to mitigate current climate change. According to the IPCC thematic report, the world needs to achieve CO_2 emissions neutrality by 2050 and with net zero emissions of all GHGs thereafter. The common plan for world development is to achieve carbon peak and neutrality by 2050. China aims to achieve peak carbon emissions by 2030 and carbon neutrality by 2060 with stronger policies and measures (UNGA-75th 2020).

The carbon footprint (CF) is an indicator used to account for carbon emissions based on the ecological footprint, primarily measuring the degree of pressure on natural resources from human activities over the entire life cycle (Wackernagel and Rees, 1998). Agricultural production is one of the major contributors to carbon emissions, 12% of total anthropogenic emissions (Walling and Vaneeckhaute, 2020). Agricultural CF refers to calculating the sum of GHG emissions and consumption "from cradle to grave" in the agricultural production system based on the life-cycle assessment (LCA) method and evaluation of the impact on climate change in the form of CO_2-eq (Wiedmann and Minx, 2008; Yan et al., 2015; Xu et al., 2020). Rice-cropping systems are a vital part of agricultural systems. In the past two decades, total rice production has increased from 160,65 to 208,49 million tons, and the total rice sowing area has increased from 265,07 to 294,50 thousand hectares in China (NBSC 2023), which is largely attributed to the rapid increase in agronomic inputs. Therefore, exploring the CF of rice-cropping systems is essential to mitigate global warming in China. Paddy fields are important sources of agricultural GHG emissions, especially CH_4 and N_2O emissions, which account for 12 ~ 26% and 7 ~ 11% of the total emissions from global agricultural fields, respectively (IPCC, 2014). Therefore, accounting for the CF of the agricultural production process is essential in China to reduce carbon emissions caused by agricultural activities. This study describes the CF and emission reduction measures of rice-cropping systems in China, with the aim of providing solutions and support for saving energy and reducing emission in rice production.

2 Carbon footprint of Paddy fields

In rice-cropping systems, CF includes indirect emissions from the production, storage, and transportation of various agricultural inputs and direct emissions from paddy fields (Zhou et al., 2023). Specifically, in rice-cropping systems, the sum of CH_4 emissions from paddy fields, N_2O emissions from nitrogen (N) application, and CO_2 emissions from respiration are called direct emissions. Moreover, rice-cropping system indirect emissions refer to GHG emissions resulting from rice production, storage, consumption, waste chains and transportation of agricultural input production, such as human inputs, fertilizers, fuel consumption, and pest and weed control.

2.1 Direct emission of CF of paddy fields

Direct GHG emissions under conventional farming account for 75.7% of total emissions, but those from organic farming account for 90.3% (Arunrat et al., 2021). Of all gases that contribute to the greenhouse effect, N_2O is the most destructive to the ozone layer, being 298 times more destructive than CO_2 by mass over a 100-year 43 time span (Tian et al., 2020). As of 2016, anthropogenic sources contributed, on average, 43% to the total N_2O emission, of which emissions from nitrogen additions in agriculture and other sectors contributed around 70% (Lal et al., 2020). The largest emissions under organic and conventional rice farming are CH_4, followed by N_2O, accounting for 45 and 10% of the overall GHG emissions of CF, respectively (Arunrat et al., 2021).

Paddy fields are considered an important source of atmospheric CH_4. CH_4 production by methanogenic bacteria is one of the end products of organic matter mineralization under anaerobic conditions (Qian et al., 2023). Extreme reduction conditions lead to the conversion of organic carbon to CH_4 through methanogenesis (Inubushi et al., 2001). The CH_4 generated in the soil undergoes dissolved diffusion through the water–air and soil–water interfaces, is lost by the ebullient, transported to the roots by diffusion, converted to gaseous CH_4 in the aerenchyma and cortex, and subsequently released to the atmosphere through plant micropores (Hussain et al., 2015; Figure 1). CH_4 is the main sources of direct emissions, accounting for 59.7 ~ 85.7% of direct emissions (Qian et al., 2023; Zhen et al., 2023). CH_4 contributed more than 60% of the total GHG emissions of the organic, rice–fish coculture, and conventional rice farming systems (Zhen et al., 2023).

N_2O production mainly result from microbial nitrogen transformations, that is, mediated by the processes of soil nitrification, denitrification, and heterotrophic reduction of nitrate-nitrogen to ammonium (Kuypers et al., 2018). Long-term flooding of paddy fields results in a unique soil profile that leads to the development of oxidizing and reducing layers within the cultivated layer (Xing et al., 2009). N_2O diffuses into the atmosphere mainly from water, plants, and the concentration gradient between soil and water (Figure 2). N_2O is released mainly through the soil surface in the absence of floodwater (Yan et al., 2000).

CO_2 emissions from paddy fields mainly come from biotic and abiotic processes, and are less than those of CH_4 and N_2O (Figure 3). Biological processes include the activity of plants and microorganisms in the soil, and abiotic processes are mainly the oxidation of carbon-containing materials in the soil. But in paddy field studies, CO_2 emission or C sequestration from soil were not considered because soil organic matter is typically maintained or increased in intensive and irrigated rice production system (Cassman et al., 1995; Bronson et al., 1997). Rice is a C3 plant with low efficiency of CO_2 assimilation, especially photorespiration. Soil CO_2 emissions are mainly derived from soil respiration. Carbon accumulation in flooded soil results in lower emissions mainly due to poor carbon oxidation (anaerobic) conditions.

2.2 Indirect emission of CF of paddy fields

In recent years, increasing attention has been given to indirect carbon emissions from rice production. Indirect carbon emissions in rice-cropping systems emanate from carbon emitted during the use of fertilizer, electricity and diesel oil, fuel combustion, machinery inputs,

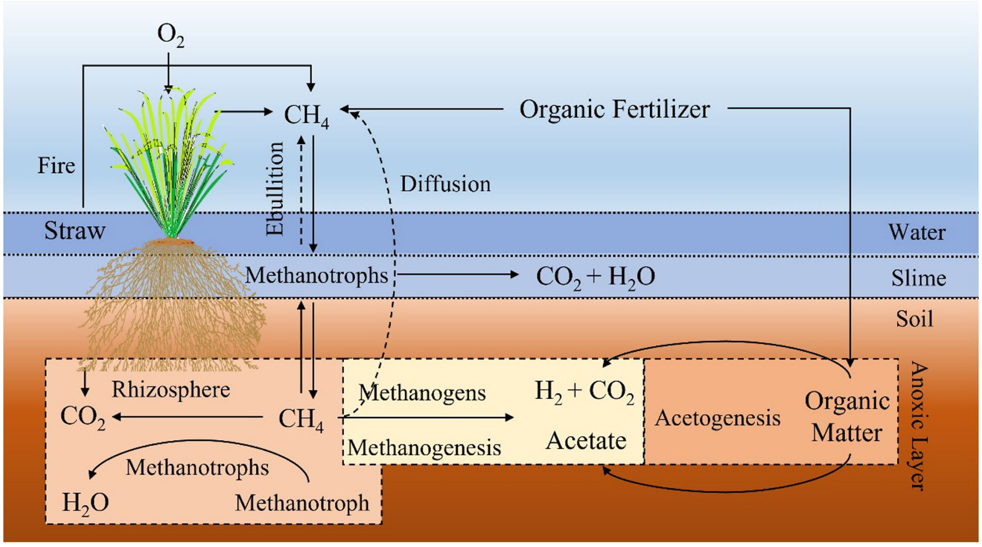

FIGURE 1
The main production process of CH_4 in paddy fields.

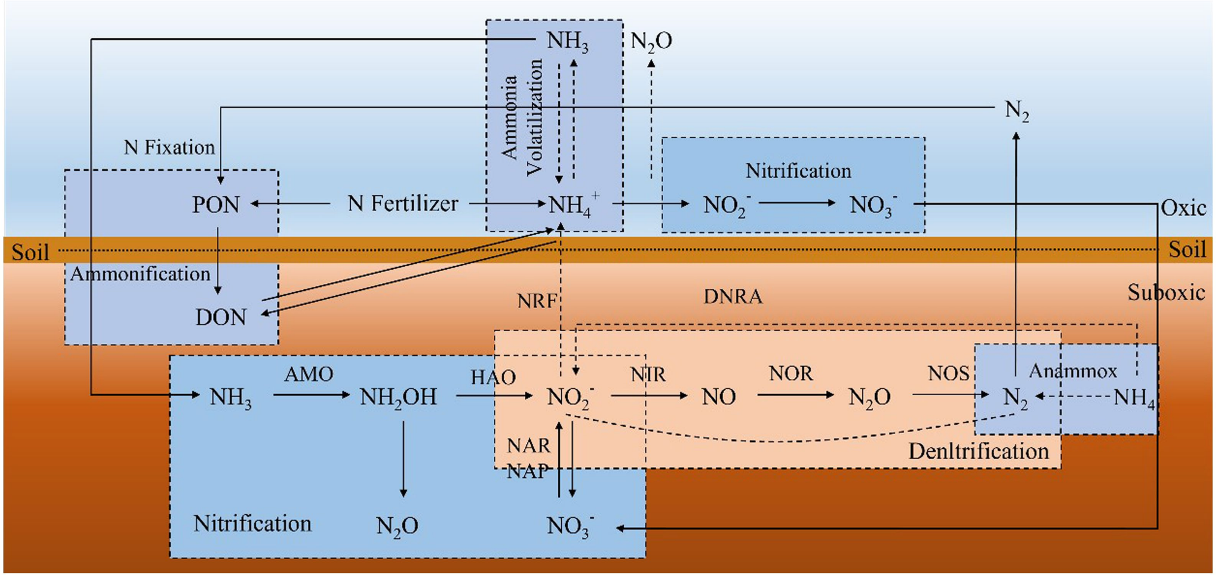

FIGURE 2
The main production process of N_2O in paddy fields.

labor, irrigation, herbicides, pesticides, seeds, trays, and other material inputs (Adviento-Borbe et al., 2007; Fuentes-Ponce et al., 2022).

Indirect GHG emissions as a percentage of total emissions under rice-based cropping systems range from 4.5 to 61.7% (Tables 1, 2). Indirect emissions under rice-cropping systems in the middle and lower reaches range from 1.86 Mt. CO_2-eq to 8.09 Mt. CO_2-eq, accounting for 23.8 ~ 34.2% of total emissions (Qin, 2011; Cheng, 2015; Xia, 2019). In the double-season rice and ratoon rice systems, indirect GHGs in the first season accounted for 11.4 ~ 17.3%, and those in the second season accounted for 5.2 ~ 6.8% of the annual total indirect GHGs (Xu et al., 2022). Urea and phosphate fertilizer (to a lesser extent) were the most responsible for increasing indirect emissions (Fuentes-Ponce et al., 2022; Table 3). The indirect emissions of CO_2 from agricultural inputs were obviously greater than those from farm operations in each cropping system. Indirect GHG emissions from agriculture inputs under fertilizer, electricity and diesel were higher than other farm inputs (Xue et al., 2016; Jiang et al., 2020; Li et al., 2020; Ling et al., 2021; Huang et al., 2022; Xu et al., 2022). Indirect emissions of GHGs arising from the production of agricultural inputs, fuel combustion, and use of machinery may contribute as much as half of the total GHG emissions (Mosier et al., 2005; Adviento-Borbe et al., 2007). In addition to fertilizers, the share of indirect GHG emissions from herbicides, labor and irrigation in addition to fertilizers was still high in multiple rice-cropping systems (Chen et al., 2020; Ghosh et al., 2022). In addition,

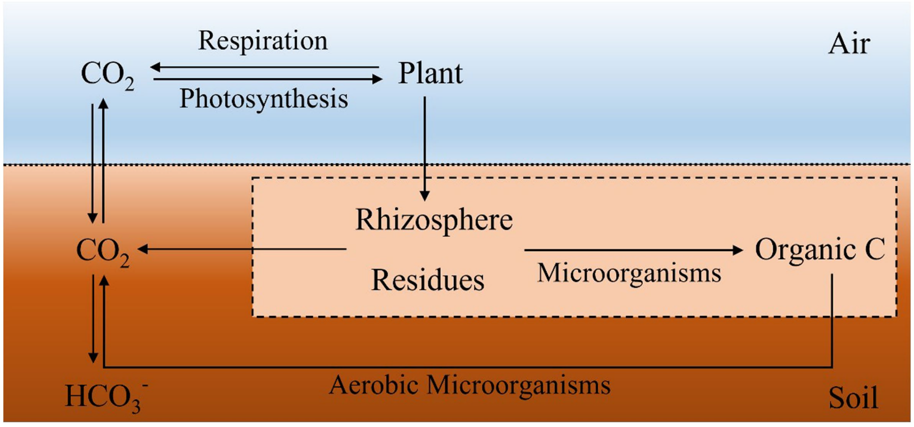

FIGURE 3
The main production process of CO_2 in paddy fields.

TABLE 1 Proportion of indirect and direct emissions in different rice-based cropping systems.

Rice-based cropping systems	$GHG_{Indirect}$ / GHG_{Total} (%)	CV	GHG_{Direct}/GHG_{Total} (%)	CV	References
Single-season rice	7.0 ~ 48.6	0.22	51.4 ~ 93.0	0.55	Xue et al. (2016), Jiang et al. (2019a,b, 2020), Sun et al. (2019), Xu et al. (2022), Qin et al. (2023)
Double-season rice	4.5 ~ 53.7	0.58	46.3 ~ 95.5	0.14	Xue et al. (2016), Sun et al. (2019), Chen et al. (2020), Jiang et al. (2020), Lin et al. (2021), Huang et al. (2022), Xu et al. (2022), Qin et al. (2023)
Ratoon rice	4.6 ~ 61.7	0.10	38.3 ~ 95.4	0.34	Huang et al. (2022), Xu et al. (2022)
Rice–fallow	15.6 ~ 56.9	0.80	43.1 ~ 82.4	0.28	Lal et al. (2020), Lin et al. (2021), Huang et al. (2022)
Rice–wheat	15.7 ~ 33.4	0.32	66.6 ~ 84.3	0.09	Chen et al. (2020), Lin et al. (2021), Ghosh et al. (2022), Huang et al. (2022)
Rice–maize	11.0 ~ 51.3	0.83	48.7 ~ 89.0	0.27	Sun et al. (2019), Jiang et al. (2020), Huang et al. (2022)
Rice–rapeseed	30.8 ~ 40.3	0.54	59.7 ~ 69.2	0.18	Lin et al. (2021), Huang et al. (2022)
Rice–fish / crayfish	23.2 ~ 48.2	0.50	51.8 ~ 76.8	0.28	Lin et al. (2021), Zhen et al. (2023)

$GHG_{Indirect}$, greenhouse gas indirect emissions, GHG_{Direct}, greenhouse gas direct emissions; GHG_{Total}: greenhouse gas emissions.

under organic and conventional rice farming treatments, conventional cultivation had the highest indirect GHG emissions of herbicides, insecticides and transportation (Arunrat et al., 2021).

3 Influencing factors of the CF of paddy fields

Variations in cropping system, cultivar., tillage type, fertilizer, irrigation, and additive substance among different cropping systems impact soil properties, microbial abundance and activity, and crop growth, leading to differences in carbon emissions (Tables 3, 4).

3.1 Cropping systems

The higher resource use efficiency and lower carbon emission in the optimized rice rotation systems can improve soil aeration and promote microorganism activity, microbial cycling, and retention of carbon and N. Under different rotation systems, Rice–maize or

TABLE 2 Proportion of indirect and direct emissions in different rice cultivation practices.

Rice cultivation practices	$GHG_{Indirect}/GHG_{Total}$ (%)	CV	GHG_{Direct} / GHG_{Total} (%)	CV	References
Conventional tillage	17.8 ~ 55.6	0.41	44.4 ~ 82.2	0.19	Xu et al. (2020), Arunrat et al. (2021), Shang et al. (2021), Ghosh et al. (2022), Kumar et al. (2022)
No tillage	36.3 ~ 55.3	0.22	44.7 ~ 63.7	0.19	Xu et al. (2020), Shang et al. (2021), Ghosh et al. (2022), Kumar et al. (2022)
Organic tillage	5.8 ~ 51.0	1.01	49.0 ~ 94.2	0.31	Arunrat et al. (2021), Zhen et al. (2023)
No straw tillage	23.3 ~ 66.1	0.50	33.9 ~ 76.7	0.38	Yadav et al. (2018), Li et al. (2020)
Straw tillage	7.5 ~ 62.6	0.72	37.4 ~ 92.5	0.36	Yadav et al. (2018), Li et al. (2020), Qin et al. (2023)

$GHG_{Indirect}$, greenhouse gas indirect emissions, GHG_{Direct}, greenhouse gas direct emissions; GHG_{Total}: greenhouse gas emissions.

rice–wheat are highly effective strategies for reducing CF and enhancing the net C sink as well as maintaining high grain yield (Janz et al., 2019; Jiang et al., 2020; Huang et al., 2022). The introduction of a rice–maize system into a double-season rice system provides a feasible system to significantly reduce the CF by 35.0 ~ 41.7% (Jiang et al., 2020). One of the reasons for this is that maize, as a C4 crop, is more yielding than C3 crops such as rice and wheat (Huang et al., 2022). On the other hand, aerobic conditions during the growing season of maize and wheat can improve the nutrient availability of the following rice by accelerating soil organic matter mineralization (Jiang et al., 2020; Huang et al., 2022). The rice–wheat rotation showed the highest total CH_4 emissions in the rice season, but total N_2O emissions were lowest compared to rice–green manure rotation and rice–fallow rotation (Hu et al., 2016; Xu, 2017). The annual CF of rice–wheat rotation is the lowest, followed by rice–shrimp cropping, and the highest is in cold-soaked rice fields ("medium rice-winter soak") (Xu, 2020). The carbon emissions per unit area and CF per unit yield of the rice season in the spring maize-late rice system were reduced by 496 kg CO_2-eq·ha^{-1} and 0.24 kg CO_2-eq·kg^{-1} compared to the double season rice, respectively (Jiang et al., 2019a,b). Higher agricultural inputs and GHG emissions resulted in a higher global warming potential (GWP) in double-season rice than in ratoon rice. Zhou et al. (2023) compared the three rice systems, and the average annual GWP of double-season rice was 152,66 kg CO_2-eq ha^{-1}, which was 104.9 and 70.2% higher than those of middle-season rice and ratoon rice systems, respectively. Similar results were also reported for ratoon rice, which had a lower CF than double-season rice (Qiao, 2019; Sun et al., 2019; Xu et al., 2022). The two experiments demonstrated that ratoon rice had a 27.4 ~ 40.7% lower annual CF than double-season rice (Huang et al., 2022; Xu et al., 2022).

Furthermore, integrated rice and aquatic animal production systems are rapidly and increasingly being developed. Choosing rice–fish, rice–duck and rice–crayfish systems can reduce GHG emissions through biological intercropping with rice (Table 5, 6; Xu, 2017; Ling et al., 2021; Jiang et al., 2022). In different integrated rice-cropping systems, the rice–duck systems increased N_2O emissions by 4.2 ~ 5.2% while reducing total CH_4 emissions from rice fields by 8.80 ~ 16.68% compared with the conventional cultivation mode (Xu et al., 2017). Given that CH_4 emission contributed to 85.83 ~ 96.22% of GWP, the great reduction in CH_4 emission led to a significantly lower GWP of the rice–duck systems. Across the two cropping systems, the CF of the rice–fish system was 0.8 times lower than that of the organic rice system (Zhen et al., 2023). In the straw return treatments of the integrated rice–crayfish system, GHG emissions were approximately 7.5% lower than those of the fallow rice system (Ling et al., 2021). The CFs were 141,26 kg CO_2-eq·ha^{-1} and 131,40 kg CO_2-eq·ha^{-1} for single rice and rice–crayfish systems, respectively, and the CF per unit production value and CF per unit nutrient density of the rice–shrimp systems were 81.4 and 49.3% lower than those of single rice, respectively (Jiang et al., 2022). The above phenomenon may be attributed that crayfish or shrimp hiding dig burrows in field, which increases the redox potential of soil and thus decreasing CH_4 emission (Ling et al., 2021; Jiang et al., 2022).

3.2 Rice variety

Rice variety is an important factor affecting GHG emissions, with differences in CH_4 and N_2O emissions between different rice varieties reaching 6 and 14 times, respectively (Riya et al., 2012). Drought-resistant rice varieties may benefit climate change mitigation and adaptation efforts, because it can reduce GHG emissions by significantly reducing irrigation water use (Luo, 2010; Serraj et al., 2011; Xu et al., 2015). The aerobic rice system saved 14.6 and 19.3% of the CF of rice production over shallow lowland rice and rice intensification systems, respectively (Dash et al., 2022). The drought resistant rice reduced CH_4, N_2O and CO_2 emissions by 21.5, 3.7 and 9.8% compared with the typical variety planted in flooded and wet intermittent irrigation, respectively (Xu et al., 2015). This phenomenon might be partly due to significant differences in the morphological characteristics, amounts of root exudates, microbial communities and plant litter decomposition among different rice varieties (Aulakh et al., 2001; Liechty et al., 2020).

Developing large panicles benefits rice production by increasing yield and produces low CH_4 emissions because rice varieties with large panicles may reduce CH_4 emissions mainly by controlling CH_4

TABLE 3 Carbon footprint (CF) in different rice-based cropping systems.

Rice-based cropping systems	CF	CV	References	CF	CV	References
	(kg CO_2-eq kg^{-1})			(kg CO_2-eq ha^{-1})		
Single-season rice	0.10 ~ 1.36	0.61	Xue et al. (2016), Jiang et al. (2019a,b, 2020), Tseng et al. (2020), Bakhshandeh et al. (2022), Xu et al. (2022)	989.2 ~ 18621.5	0.74	Jiang et al. (2019a,b, 2020), Tseng et al. (2020), Leon et al. (2021), Leon and Izumi (2022), Alam et al. (2023)
Double-season rice	0.83 ~ 4.10	0.56	Xue et al. (2016), Sun et al. (2019), Chen et al. (2020), Jiang et al. (2020), Mandal et al. (2021), Shang et al. (2021), Qin et al.(2023)	10260.0 ~ 42213.0	0.43	Sun et al. (2019), Chen et al. (2020), Jiang et al. (2020), Lin et al. (2021), Shang et al. (2021), Xu et al. (2022), Alam et al. (2023), Qin et al. (2023)
Ratoon rice	2.84 ~ 3.56	/	Xu et al. (2022)	11548.0 ~ 18621.5	0.33	Huang et al. (2022), Xu et al. (2022)
Rice–fallow	0.31 ~ 0.80	0.51	Huang et al. (2019), Lal et al. (2020)	6431.5 ~ 13806.0	0.85	Huang et al. (2019, 2022), Lal et al. (2020), Ling et al. (2021)
Rice–wheat	0.58 ~ 1.10	0.27	Chen et al. (2020), Li et al. (2020), Ghosh et al. (2022), Zhang et al. (2022)	5178.0 ~ 22488.0	0.59	Chen et al. (2020), Li et al. (2020), Lin et al. (2021), Ghosh et al. (2022), Huang et al. (2022), Zhang et al. (2022)
Rice–maize	0.81 ~ 2.01	0.60	Sun et al. (2019), Jiang et al. (2020)	9534.3 ~ 33858.0	0.74	Sun et al. (2019), Jiang et al. (2020), Huang et al. (2022)
Rice–rapeseed	1.08	/	Huang et al. (2019)	10541.1 ~ 18328.5	0.06	Huang et al. (2019, 2022), Lin et al. (2021)
Rice–fish / crayfish	0.54	/	Zhen et al. (2023)	17857.2 ~ 19736.8	/	Lin et al. (2021)

production (Das and Baruah, 2010; Jiang et al., 2016). The more rice tiller number, stems and leaves the plant has the greater the rate of rice plant-mediated transport, thus promoting CH_4 emissions. Research has shown that CH_4 emissions are positively correlated with the rice plant height, and the CH_4 emissions of taller varieties with a plant height of 120 cm are 2.9 times higher than those of shorter varieties with a plant height of 90 cm (Ding et al., 1999). This phenomenon occurs because the oxidizing effect on CH_4 is greater than the production and transport effects in high rice plants. Therefore, short-stalked rice varieties are more advantageous than tall-stalked rice varieties for regulating carbon emissions.

Furthermore, high-yielding varieties are in fact also emission-reducing varieties, mainly by changing photosynthetic product allocation to improve the harvest index and reduce the carbon source required by methanogenic bacteria (Chen, 2017). A strongly CO_2-responsive cultivar (hybrid rice) was observed to significantly reduce GHG emissions (Yu et al., 2021; Qiu et al., 2023). Higher content of dissolved organic matter, dissolved sugars, NH_4-N, and NO_3-N in Yongyou 1,540 varieties reduced microbial abundance and CF (Ding et al., 2022). In addition, strongly CO_2-responsive rice can distribute photosynthetic products more fully to the roots to increase the C/N, promote the conversion of N fertilizer to microbial N and inhibit N_2O from nitrification and denitrification. In terms of response to x [CO_2], the strongly CO_2-responsive rice cultivar could reduce N_2O emissions by 38.3 ~ 41.9% relative to the weakly CO_2-responsive cultivar (Yu et al., 2021).

3.3 Agronomic practices

3.3.1 Tillage

In addition to the influence of rice-cropping systems and variety, agronomic practices of soil conditions are more influential. Different tillage practices significantly affect soil respiration and the surface and subsurface microenvironments, leading to changes in soil organic carbon fixation and carbon emissions. Conservative tillage reduces the inefficient evaporation of soil water, thus reducing the irrigation of crop water requirements improving water use efficiency and ultimately reducing carbon emissions (Follett, 2001; Shang et al., 2021; Ghosh et al., 2022). Conservative tillage, which aims at minimize carbon costs and resource use efficiency, has led to significant reduction in total estimated GHG emissions and improved carbon efficiency (Das et al., 2020; Gangopadhyay et al., 2022; Ghosh et al., 2022). The no-till approach resulted in a higher content of macroaggregates, which favored the production of more N_2O for denitrification to proceed, and straw incorporation provided more reaction substrate for

TABLE 4 Carbon footprint (CF) in different rice cultivation practices.

Rice cultivation practices	CF	CV	References	CF	CV	References
	(kg CO_2-eq kg^{-1})			(kg CO_2-eq ha^{-1})		
Conventional tillage	0.31 ~ 2.94	0.78	Yadav et al. (2018, 2020), Huang et al. (2019), Xu et al. (2020), Mandal et al. (2021), Shang et al. (2021), Du et al. (2022), Ghosh et al. (2022), Zhen et al. (2023)	1292.0 ~ 19677.5	1.04	Yadav et al. (2018, 2020), Huang et al. (2019), Xu et al. (2020), Shang et al. (2021), Ghosh et al. (2022), Kumar et al. (2022)
No tillage	0.28 ~ 3.47	1.16	Yadav et al. (2018, 2020), Huang et al. (2019), Xu et al. (2020), Mandal et al. (2021), Shang et al. (2021), Ghosh et al. (2022), Qin et al. (2023)	1080.0 ~ 20401.0	1.05	Yadav et al. (2018, 2020), Huang et al. (2019), Xu et al. (2020), Shang et al. (2021), Ghosh et al. (2022), Kumar et al. (2022), Qin et al. (2023)
Organic tillage	0.39	/	Zhen et al. (2023)	3570.4 ~ 13005.0	1.04	Arunrat et al. (2021), Zhen et al. (2023)
No straw tillage	0.30 ~ 0.99	0.03	Yadav et al. (2018), Li et al. (2020), Mandal et al. (2021)	1986.0 ~ 15399.1	0.55	Yadav et al. (2018), Hung et al. (2019), Li et al. (2020)
Straw tillage	0.29 ~ 3.91	0.87	Yadav et al. (2018, 2020), Huang et al. (2019), Li et al. (2020), Mandal et al. (2021), Shang et al. (2021), Du et al. (2022), Qin et al. (2023)	1112.0 ~ 21267.6	1.00	Yadav et al. (2018, 2020), Hung et al. (2019), Li et al. (2020), Shang et al. (2021), Qin et al. (2023)

denitrification, but residual nutrients were released into the atmosphere by burning to CO_2 (Freibauer et al., 2004; López-Fando and Pardo, 2011). Dry direct-seeding and transplanting showed significant differences in CH_4 emissions and GWP but not N_2O emissions compared with wet direct-seeding (Hang, 2015). Tillage destroys the original structure of the soil and accelerates soil disturbance and soil organic matter decomposition, causing changes in soil redox potential and soil moisture, promoting soil carbon emissions, and reducing the oxidation of methane by the soil (Meng et al., 2006).

3.3.2 Fertilizer

Soil CF is greatly influenced by the type and structure of fertilizer application, the amount of fertilizer applied and the mix of different fertilizers. The CF of rice production were positively correlated with N fertilizer rates. Fertilizer is the main sources of indirect emissions, accounting for 41.1 ~ 75.9% of indirect emissions. GHG emissions from fertilizers account for 17.54 ~ 88.39% of indirect emissions in different rice-based cropping systems (Tables 3, 4; Supplementary Tables S1, S2). Fertilizer application indirectly affects gas emissions by influencing soil pH, Eh, temperature and bacterial concentration. Urea application reduces plant residues and soil organic matter and promotes the decomposition of organic matter, while urea itself is gradually hydrolyzed in the soil and inhibits oxidation, increasing emissions (Cai, 2009).

The mitigation of soil CH_4 and N_2O emissions under urea deep placement decreased the total GHG emissions by 34.0% and the CF by 46.0% (Liou et al., 2003). The application of inorganic N fertilizer significantly promoted rice field emissions, mainly because increasing the soil N content provided a substrate for the nitrification denitrification process and influenced the nitrification denitrification reaction process (Gregorich et al., 2005; Xiang et al., 2007; Ma et al., 2010). Nitrate N had some inhibitory effect on CH_4 oxidation capacity, but compared to nitrate N fertilizers, long-term application of ammonium N can reduce CH_4 oxidation capacity by tens of times (Liou et al., 2003; Yang et al., 2010). Foliar N fertilization not only reduces fertilizer losses but also reduces CH_4 and N_2O emissions (Das and Adhya, 2014). The method of fertilizer application and the amount of fertilizer applied also affect the carbon footprint of rice fields. Chemical fertilizer application reduced CH_4 emissions when N phosphorus (P), and potassium (K) levels were essentially constant, while additional organic fertilizer application promoted emissions (Nan et al., 2020). The CF of the rice-cropping system varied significantly among fertilizer combinations, and N and K application and N, P, and K application were 2.9 and 38.2% lower than no fertilizer application, respectively (Qin et al., 2023). However, the positive effect of fermented digestate (organic fertilizer) on CH_4 emissions from paddy fields was also much lower than that of "fresh" organic fertilizer. Soil CO_2 emissions showed a decreasing trend with increasing N application levels in the range of 0 ~ 270 kg N ha^{-1} (Wilson and Al-Kaisi, 2008). Thus, the timing of fertilizer, N deep placement, balanced inorganic fertilization, foliar N fertilization, nitrate N, and ammonium N can increase grain yield, reduce CF, and enhance the net ecosystem economic benefit from rice fields (Yang et al., 2010; Das and Adhya, 2014; Liu et al., 2020).

TABLE 5 Share of source-wise greenhouse gas (GHG) indirect emissions (%) in different rice-based cropping systems.

Rice-based cropping systems	Fertilizers (%)	CV	Diesel (%)	CV	Electricity (%)	CV	Pesticides[a] (%)	CV	Seeds (%)	CV	Others (%)[b]	CV	References
Single-season rice	39.4 ~ 77.5	0.46	3.1 ~ 15.2	0.93	2.9 ~ 36.3	1.21	1.7 ~ 6.2	0.82	2.9 ~ 3.8	0.20	5.3 ~ 11.7	0.53	Xue et al. (2016), Jiang et al. (2019a,b),
Double-season rice	40.5 ~ 80.9	0.29	4.5 ~ 30.1	0.68	1.3 ~ 38.6	1.00	0.8 ~ 5.3	0.61	2.4 ~ 27.6	1.19	0.9 ~ 13.6	0.90	Xue et al. (2016), Chen et al. (2020), Jiang et al. (2020), Huang et al. (2022), Xu et al. (2022)
Ratoon rice	67.6 ~ 73.6	0.06	3.9 ~ 7.3	0.43	2.8 ~ 14.4	0.96	2.4 ~ 3.2	0.21	2.3 ~ 20.7	1.14	1.8 ~ 11.0	1.01	Huang et al. (2022), Xu et al. (2022)
Rice–fallow	49.6 ~ 64.3	0.18	3.2 ~ 24.9	1.09	3.9 ~ 11.1	0.68	5.4 ~ 8.4	0.31	5.9 ~ 20.9	0.79	1.9 ~ 9.3	0.91	Lal et al. (2020), Huang et al. (2022)
Rice–wheat	37.2 ~ 62.9	0.27	3.9 ~ 16.5	0.60	2.4 ~ 21.5	0.74	1.4 ~ 8.9	0.71	5.5 ~ 21.3	0.83	3.9 ~ 14.0	0.72	Chen et al. (2020), Lal et al. (2020), Ghosh et al. (2022); Huang et al. (2022)
Rice–maize	50.8 ~ 67.5	0.20	2.9 ~ 15.4	0.96	3.2 ~ 25.4	1.10	4.8 ~ 5.2	0.06	2.6 ~ 20.4	1.10	1.2 ~ 2.0	0.35	Jiang et al. (2020), Huang et al. (2022)

[a] Pesticides, herbicides, insecticides, and fungicides.

[b] Contains seeds, films, labor, and machinery, etc.

TABLE 6 Share of source-wise greenhouse gas (GHG) indirect emissions (%) in different rice cultivation practices.

Rice cultivation practices	Fertilizers (%)	CV	Diesel (%)	CV	Electricity (%)	CV	Pesticides (%)[a]	CV	Seeds (%)	CV	Others (%)[b]	CV	References
Conventional tillage	37.9 ~ 80.4	0.36	2.5 ~ 45.3	0.94	2.9 ~ 19.0	0.68	1.3 ~ 6.2	0.51	2.0 ~ 4.1	0.28	2.0 ~ 28.4	1.01	Yadav et al. (2018), Xu et al. (2020), Shang et al. (2021), Ghosh et al. (2022), Kumar et al. (2022), Qin et al. (2023)
No tillage	39.9 ~ 84.5	0.29	2.0 ~ 8.1	0.46	3.0 ~ 17.5	0.57	1.8 ~ 10.2	0.71	2.1 ~ 5.0	0.58	1.5 ~ 20.0	1.05	Yadav et al. (2018), Shang et al. (2021), Ghosh et al. (2022), Kumar et al. (2022)
No straw tillage	22.5 ~ 37.7	0.36	5.4 ~ 37.5	1.06	0.3 ~ 12.5	1.35	1.0 ~ 5.5	0.99	1.0 ~ 6.3	1.03	12.7 ~ 12.7	0.01	Li et al. (2020), Huang et al. (2019)
Straw tillage	17.5 ~ 88.4	0.56	6.2 ~ 51.7	1.14	0.2 ~ 15.2	1.30	0.8 ~ 11.3	0.90	0.8 ~ 4.9	0.70	2.6 ~ 9.9	0.57	Huang et al. (2019), Li et al. (2020), Shang et al. (2021), Ghosh et al. (2022), Qin et al. (2023)

[a] Pesticides, herbicides, insecticides, and fungicides.

[b] Contains seeds, films, labor, and machinery, etc.

3.3.3 Irrigation

Irrigation, as the second largest source of carbon inputs, was approximately 22% of total carbon inputs in crop production in China over 1993–2007 (Cheng et al., 2011). Gas emissions from electricity used for irrigation account for 1.27 ~ 38.64% of total indirect emissions (Tables 3, 4). Continuous irrigation creates an anaerobic environment in paddy soils to promote GHG emissions. The combined greenhouse effects of irrigation practices that conserve water, such as intermittent irrigation and moist irrigation profiles, were only 10% of those under continuous flooding (Jiang et al., 2023; Maris et al., 2015). Nitrification and denitrification processes are directly influenced by soil moisture, and proper water content can promote both nitrification and denitrification. Intermittent irrigation has been shown to be an effective measure to reduce emissions by alternating anaerobic and aerobic environments in paddy fields changing the redox potential of the soil to reduce GHG emissions (Xu et al., 2015). The most striking difference is that alternate wetting and drying irrigation reduced the CF, while continuous flooding irrigation CF showed an increase of 1.86 times (Du et al., 2022). Compared to conventional flooding paddies, maintaining a saturated soil water content and maintaining 80% of the field capacity significantly reduced the CF by 30.7 and 34.7%, respectively (Xu et al., 2020).

3.3.4 Additive substances

There are also many proven farming management practices that can sequester carbon and reduce emissions in rice ecosystems. For example, biochar addition during the rice growing season reduces GHG emissions (Woolf et al., 2010; Xie et al., 2013; Qi et al., 2020). Research findings suggest that the application of biochar in the rice–wheat system significantly decreases CH_4 and N_2O emissions by 11.2 ~ 17.5% and 19.5 ~ 26.3%, respectively (Wu et al., 2019). The application of biochar to farmland can reduce GHG emissions while cultivating soil carbon pools, thereby improving crop quality and achieving high ecological and environmental benefits (Ge et al., 2020; Qi et al., 2020). In addition, one of the most effective ways to reduce GHG emissions from rice paddies is by using methane inhibitors (essentially humic acid), which accelerate the conversion of soil organic matter to humus, thereby significantly reducing the substrate suppression emissions required for methane formation. The annual accumulation of CH_4 in green manure–rice significantly reduced the CF, mainly because green manure reduced the abundance of methanogens by reducing the soil C/N ratio (Zhong et al., 2021). Furthermore, plastic film mulching could also significantly reduce GHG emissions (Berger et al., 2013; Gao et al., 2014).

4 Emission mitigation options in rice-cropping systems

Agricultural carbon sequestration and emission reduction has received a great deal of attention at home and abroad as an important way to effectively mitigate the greenhouse effect. As an important source of GHG emissions, paddy fields pose a serious threat to global warming. Therefore, for the sustainable development of mankind, control of GHG emissions from paddy field rice-cropping systems is urgently needed. Carbon sequestration and reduction could be considered from soil, energy consumption and plants in rice-cropping systems (Figure 4). Evidently, reasonable mitigation measures for direct and indirect emission impact factors are essential.

In the past few decades, China has made fruitful achievements in cropping systems, rotation systems, and integrated cropping systems, which are prerequisites for climate change mitigation in agriculture. To reduce farmland emissions by adjusting the cropping structure, reducing the proportion of winter fallow fields and increasing the proportion of straw returned to the field are practical and feasible technical ways to further improve the carbon sequestration potential of rice-cropping systems. The ratoon rice exhibited the lowest GHG intensity among the single-season and double-season rice, which showed that ratoon rice is a cropping system with relatively high yield and low GHG emissions (Zhou et al., 2023). Considering the reduction in inputs and GHG emissions but the high economic efficiency of ratoon rice systems, ratoon rice is recommended to grow in the region where thermal energy is more than that required for planting single-season rice but not enough for planting double-season rice (Qiao, 2019; Xu et al., 2022; Zhou et al., 2023). In addition, the replacement of rice–follow with rice–maize, rice–wheat, rice–fish, rice–duck or rice–crayfish are highly effective strategies for reducing CF as well as maintaining high grain yield (Janz et al., 2019; Jiang et al., 2020; Huang et al., 2022).

Innovative varieties for rice have been developed to conserve nutrients, energy, and water to achieve sustainable yields and mitigate GHG emissions. Noteworthy, for the short-term reduction of GHG emissions, aerobic rice, large panicle size rice and drought resistant rice varieties are good options (Luo, 2010; Serraj et al., 2011; Xu et al., 2015; Yun et al., 2019; Dash et al., 2022). In addition, hybrid rice is great option, for instance strongly CO_2-responsive cultivars and high-yielding varieties (Qiu et al., 2023). Therefore, mastering the characteristics and development trend of variety renewal and technology improvement can provide a scientific basis for high-yielding low-carbon rice crop technology innovation.

Low-carbon rice management techniques such as no-till, conservation tillage rice, deep application of N fertilizer, residue retention and intermittent water-saving irrigation can enhance the soil agglomeration structure to reduce CF. Determining the fertilizer application ratio according to the growth needs of rice combined and delaying the application period of N fertilizer can also reduce N_2O emissions, while the reduction of GHG emissions from rice fields can also be achieved by applying controlled release fertilizers and additives. In addition, nitrate N, urea N and slow-release fertilizers with high N utilization and emission reduction should be selected, and techniques such as off-root fertilization should be used to reduce GHG emissions due to soil microbial activity (Freibauer et al., 2004; López-Fando and Pardo, 2011; Hang, 2015). In terms of irrigation, the use of intermittent irrigation and moist irrigation profiles, can also reduce the CF (Jiang et al., 2023; Maris et al., 2015). In addition, biochar, methane inhibitors and mulching plastic film can also alleviate GHG emissions (Woolf et al., 2010; Xie et al., 2013; Qi et al., 2020; Zhong et al., 2021).

In addition to reducing emissions in terms of cropping systems, variety, and agronomic practices, emission reduction measures can also be considered in terms of indirect emissions. Indirect emissions from electricity for irrigation and labor inputs are just behind fertilizer inputs (29.2 ~ 41.1%), accounting for 16.3 ~ 33.9% and 21.0 ~ 29.3% of

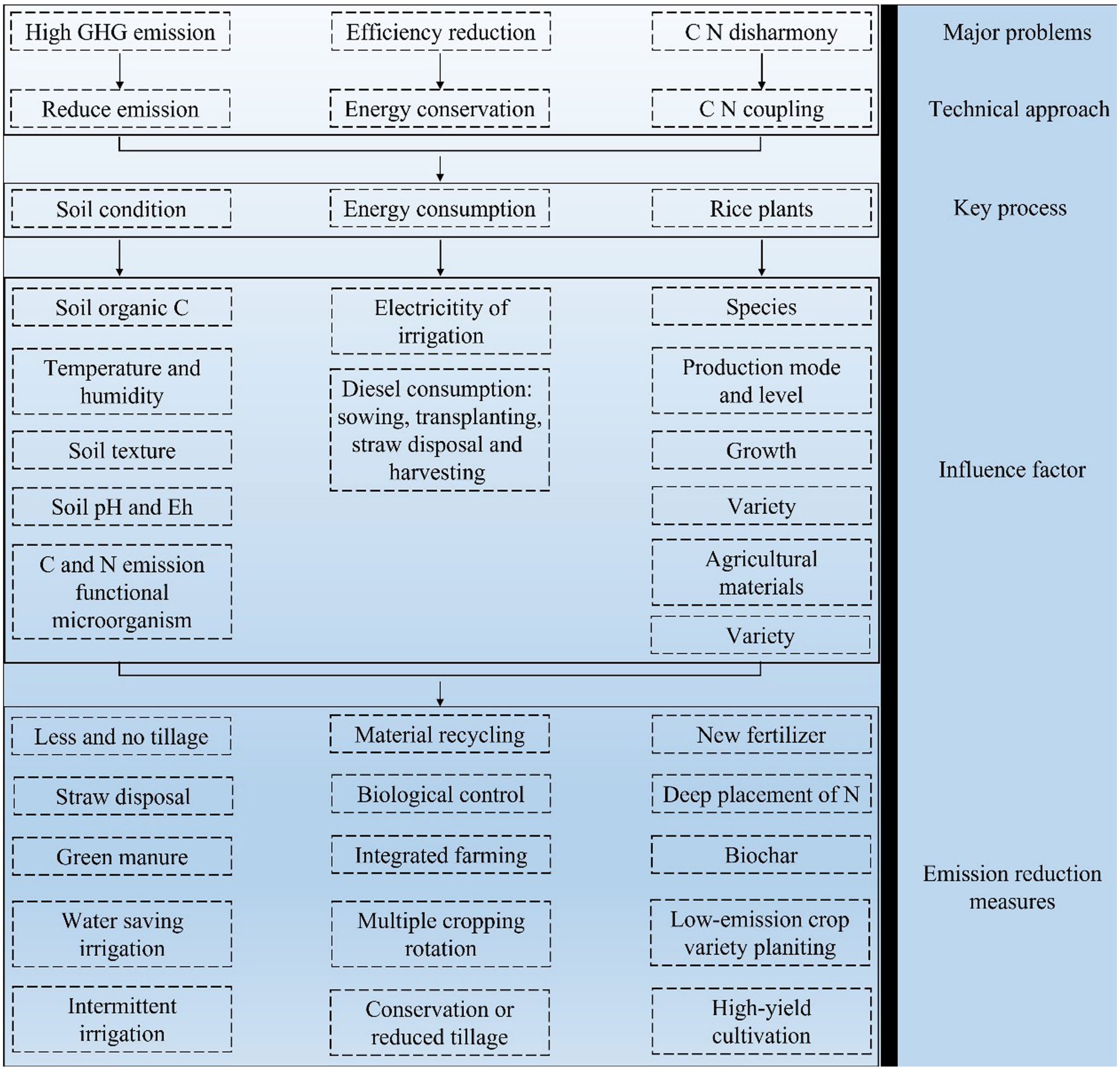

FIGURE 4
Carbon sequestration and emission reduction for paddy fields.

indirect emissions, respectively (Chen et al., 2020). Therefore, decreased GHG emissions from the rice-cropping system can be selecting varieties, reducing the use of fertilizers, especially nitrogen fertilizer, irrigation water and tillage.

5 Conclusion and prospects

The CF is influenced by the rice-based cropping systems, varieties, tillage methods, fertilizer types, irrigation conditions, and added emission reduction materials of the rice crop systems. Emissions can be reduced in rice-cropping systems by implementing the following six strategies: (1) choose ratoon rice, rice–maize, rice–wheat, rice–fish, rice–duck, and rice–crayfish cropping systems; (2) choose aerobic rice, large panicle size rice, drought-resistant rice, and the strongly CO_2-responsive rice cultivar; (3) choose deep N placement, balanced inorganic fertilization, nitrate N, ammonium N, and slow-release fertilizers; (4) choose no-till, wetting and drying irrigation, and intermittent irrigation methods; (5) add methane inhibitors and mulching plastic film; and (6) reduce farm machinery fuel consumption, electrical energy, labor inputs and disease control inputs. However, farmers are currently focusing on economic efficiency, so future research will focus on how to reduce GHG emissions while ensuring profitability for different rice-cropping systems. Additionally, understanding the social drivers of GHG emissions in rice-cropping systems is one of the future research directions.

Data availability statement

All data analyses were performed with licensed software, and generated or analyzed during this study are included in this published article.

Author contributions

YJ: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. YZ: Conceptualization, Funding acquisition, Supervision, Writing – review & editing. ZL: Conceptualization, Supervision, Writing – review & editing. KF: Supervision, Writing – review & editing. XS: Supervision, Writing – review & editing. YX: Funding acquisition, Supervision, Writing – review & editing. WW: Data curation, Funding acquisition, Methodology, Project administration, Supervision, Visualization, Writing – review & editing. HZ: Data curation, Methodology, Project administration, Supervision, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1375092/full#supplementary-material

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