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1 Introduction

Rice is a nutritious staple crop for over half of the global population, even though rice fields cover only 9% of global cropland (Maclean et al., 2002). Rice paddies are widely distributed from tropical to temperate climatic regions on all continents (except Antarctica), with high concentrations in South-East Asia. Global rice demand is predicted to grow by around 28% by

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2050 compared to the early 2000s (Alexandratos and Bruinsma, 2012). Paddy rice soils are important carbon (C) sinks, compared with upland soils, since the anaerobic conditions in flooded rice paddies slow down organic matter (OM) decomposition, consequently favoring soil organic carbon (SOC) stock increases (Yan et al., 2013; Chen et al., 2021).

However, due to cultivation under submerged conditions, rice cropping fields act as major greenhouse gas (GHG) emission sources in the form of methane (CH_4) and nitrous oxide (N_2O). Globally, 8.2% of anthropogenic CH_4 (which has 28 times higher global warming potential (GWP) than carbon dioxide (CO_2) over a 100-year period; IPCC, 2013) is emitted from rice cultivation (Saunois et al., 2020). IPCC estimated an average of 0.3% of applied nitrogen (N) to be converted into N_2O which has 298 times higher GWP than CO_2 over a 100-year period (Klein et al., 2006; IPCC, 2013). However, total N_2O flux from rice paddies has not been properly accounted for.

SOC stock is significantly affected by agricultural management practices (i.e. crop rotation, fertilizer and organic amendment applications, irrigation, tillage management, etc.) (Windeatt et al., 2014; Vicente-Vicente et al., 2016; Paustian et al., 2019; see also Chapter 16 of this book). The periodic application of organic amendments (i.e. crop residues, farmyard and livestock manure, compost, biochar, etc.) is accepted as the most beneficial practice to increase SOC stock in upland soils (Goyal et al., 1999; Diacono and Montemurro, 2011; Huang et al., 2014). In paddy rice soils, cover cropping and straw recycling were historically recommended to increase SOC stock and improve soil quality.

However, as noted, the anaerobic conditions of paddy rice systems facilitate microbial methanogenesis and convert rice paddies into a main CH_4 emission source (Chen et al., 2013), particularly after OM applications under flooded conditions (Hwang et al., 2017; Jiang et al., 2019; Song et al., 2021). Rice has the highest GHG intensity (GHGI) which indicates net GWP per grain yield among major cereal crops (Linquist et al., 2012; Carlson et al., 2017). In particular, management practices intended to increase SOC stocks, such as organic and/or inorganic fertilizer use can provide energy sources and/or substrates for methanogens and denitrification in anaerobic soils, and thus amplify GHG emissions during rice cultivation (Neue et al., 1996; Le Mer and Roger, 2001; Lee et al., 2020a,b). This should be considered for mitigation of global warming through enhancing soil C sequestration (Lee et al., 2020a,b; Song et al., 2021). In rice paddies, the overall changes of SOC stock and GHG fluxes should be estimated together when evaluating the impact of agricultural management practices on environmental sustainability.

In this chapter, we present the specific conditions leading to high SOC stocks and low CH_4 and N_2O emissions of paddy rice soils. We indicate how to evaluate their GWP considering both SOC stock and GHG emissions under different management practices.

2 Carbon sequestration potential of rice paddy soils

Rice paddy soils have a significant potential to sequester atmospheric CO_2 through increasing SOC storage (Lal, 2004; Pan et al., 2004; Yan et al., 2013; Chen et al., 2021). According to a recent global meta-analysis (Liu et al., 2021), rice paddy harbors over 14% of land SOC stocks, proportionally more than any other crop type (Table 1), mainly due to higher biomass productivity and reduced OM decomposition under anaerobic conditions. The SOC sequestration potential of rice is, at 401 kg C ha^1 year^1, much higher than that of barley, corn, and wheat residues, which amounts to 247 kg C ha^1 year^1, 292 kg C ha^1 year^1, and 272 kg C ha^1 year^1, respectively (Fig. 1) (Jarecki and Lal, 2003).

Rice paddies are flooded before transplanting, and water is drained several days before harvesting. In traditional rice cropping systems, the soil is managed under submerged conditions for at least 85–90% of the cropping period. Under these soil conditions, both the mineralization of OM inputs and decomposition of native SOC are slower than those under upland soil conditions (Witt et al., 2000). Indeed, under anaerobic conditions, OM decomposition partially affects labile compounds whilst recalcitrant aromatic and aliphatic compounds accumulate (Herndon et al., 2015). This leads to changes in SOC quality and may slow down soil organic matter (SOM) decomposition in flooded paddy soils. In addition, the formation of recalcitrant complexes with OM can make them less available for microbial decomposition (Six et al., 2002). Moreover, biological N fixation, coupled with decreased overall humification and higher primary productivity, could lead to a net accumulation of SOM (Liu et al., 2018). On the other hand, the availability of biologically fixed N may also provide substrates for N_2O emissions under reduced conditions.

In rice paddy fields, hydrologic regimes that rotate periodical flooding and drying may drive iron (Fe) cycling (Sahrawat, 2004) and thereby impact the formation of organo-mineral interactions, which were shown to be stable SOM forms in upland soils. Under the dried soil condition, Fe species may be oxidized, and during the flooding period, Fe species may be reduced. Fe cycling has the potential to stabilize SOC and reduce C oxidation and CH_4

Table 1 Estimates of global land use and SOC storage

Ecosystem	Global area (ha)	Contribution of rice paddy (%)	Mean SOC stock (Mg ha^1)		Global SOC storage (Pg C)		
			0–30 cm	0–100 cm	0–30 cm	0–100 cm	Contribution of rice paddy (%)
All soils	1.49×10^{10}	1.1	45	98	710	1456	1.2
Cropland	1.87×10^{9}	8.9	41	89	58.4	127	14.2
Rice paddy	1.67×10^{8}	-	51	108	8.5	18.0	-

Note: Data was modified from Liu et al. (2021).

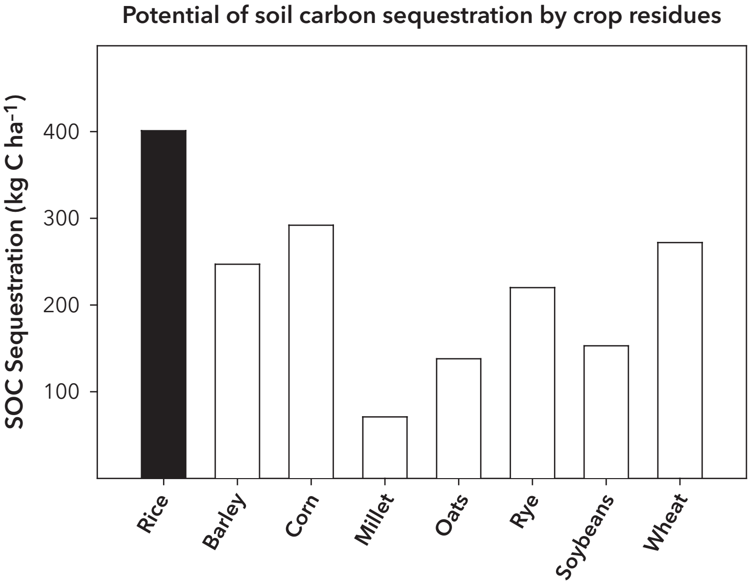

Figure 1 Potential of SOC sequestration by crop residues. (Data was modified from Jarecki and Lal, 2003.)

formation by reacting as an oxidizing agent and an electron acceptor for microbial respiration. In contrast, the formation of SOM can be maximized in partially oxidizing environments. High mineralization rates occur under completely aerobic conditions, but oxidative polymerization is favored by lack of oxygen (O_2). Therefore, repeated wetting and drying prevent the stagnation that appears in either oxidizing or reducing environments and promotes the oxidative polymerization that stabilizes OC compounds in soils (Post et al., 2004). These processes may have led to the net retention of OM and plant debris in most wetland soils (Mitsch and Gosselink, 2007).

3 Methane production, oxidation and emissions in rice paddy soils

Flooded rice paddy fields are an important anthropogenic CH_4 emission source (Newton, 2016; Nisbet et al., 2016; Saunois et al., 2016; Schaefer et al., 2016). Global CH_4 emissions from rice fields were estimated at an average of 30 Tg CH_4 year^{-1}, accounting for around 8.2% of total anthropogenic CH_4 emissions (average 364 Tg CH_4 year^{-1}) (Saunois et al., 2020). Rice production has been estimated as increasing from 97 million tons in 1990 to a predicted 145 million tons by 2025, leading to an estimated proportionate CH_4 flux increase of 1.1% per year from paddy rice systems (Anastasi et al., 1992).

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CH_4 flux in rice fields is the result of the difference between CH_4 production and consumption (oxidation). Soil flooding prevents gas exchange between the soil and the atmosphere. Methane is formed by methanogens under extremely anaerobic conditions (less than −200 mV of E_h value), and this CH_4 can also be oxidized by methanotrophs at conditions over −200 mV of soil E_h value (Garcia et al., 2000; Conrad, 2007). Rice fields are generally flooded during the cropping season while being kept dry during a succeeding fallow season. In addition, a small amount of CH_4 is oxidized during the dry fallow season, but this flux is not comparable with the big CH_4 fluxes during the flooded rice cultivation period (Fig. 2). At the early rice growth stage, CH_4 is emitted at a lower rate, but its flux steadily increases with plant growth and development of anaerobic soil conditions (Ali et al., 2009a; Kim et al., 2015; Haque et al., 2016; Jeong et al., 2018; Song et al., 2019; Lee et al., 2020a,b; Song et al., 2021).

Methanogenesis is strongly affected by the availability of C substrates, and therefore OM addition strongly stimulates CH_4 formation. Under anaerobic conditions where nitrate (NO_3^-) and sulfate (SO_4^{2-}) concentrations are low, OM [$(CH_2O)_n$] can be completely mineralized into CH_4 and CO_2 via methanogenic fermentation (Le Mer and Roger, 2001). This change needs successive reactions from four populations of microorganisms that degrade complex organic molecules into simpler compounds:

- hydrolysis of polymeric organic compounds into monomers by a hydrolytic microflora;
- acidogenesis by a fermentative microflora;
- acetogenesis by a homoacetogenic or syntrophic microflora;
- CH_4 formation by methanogens.

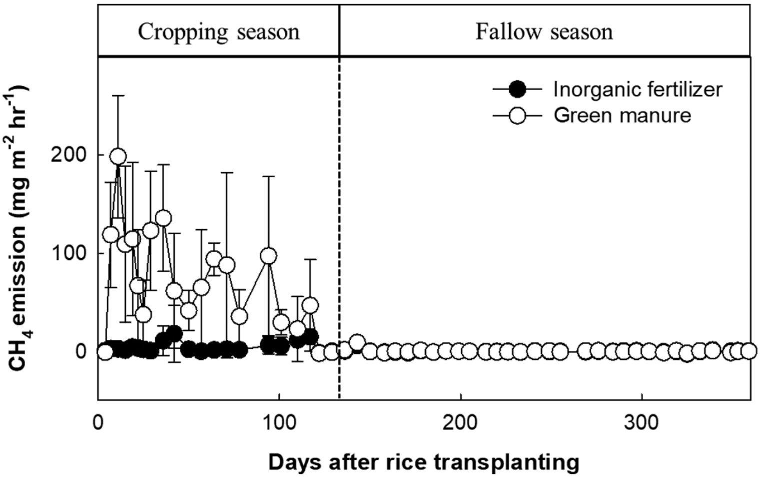

Figure 2 Annual changes of CH_4 emission rate in a mono-rice paddy.

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Methanogens belonging to the Archaea domain (Woese et al., 1978) include strictly anaerobic, specialized microflora that can develop in synergy with other anaerobic bacteria. The two major pathways of CH_4 formation are acetotrophic and hydrogenotrophic (Schütz et al., 1989). In paddy rice soils, acetotrophy is believed to be responsible for approximately two-thirds of the CH_4 produced (Le Mer and Roger, 2001).

Methane is consumed in soils by microbial oxidation. This reaction takes place in the aerobic zone of dried soils and methanogenic soils. In dried rice paddies, small amounts of CH_4 can be oxidized mainly during the fallow season. Methanotrophy is most highly developed in soils that are often water saturated or submerged and where methanogenic activity develops (Nesbit and Breitenbeck, 1992). Paddy soils for rice cultivation often have a very high potential for methanotrophic activities. However, rice paddies generally have a positive balance between CH_4 production and oxidation and consequently react like a huge CH_4 source, not a sink (Table 2).

In rice fields, variations in CH_4 flux are mainly caused by differences in methanotrophic bacteria activity (Schütz et al., 1989; Sass et al., 1990). The contribution of CH_4 oxidation to the net CH_4 budget varies, depending on agricultural practices like the management of irrigation water and organic amendments. Methanogens and methanotrophs are ubiquitous, and both population densities have a highly positive correlation with each other. It is known that cultivable methanotroph densities and potential methanotrophic activities are greater than cultivable methanogen densities and potential methanogenic activities (Joulian et al., 1997).

Methane is oxidized by two different methanotrophs (high and low CH_4 affinity). In general, O_2 availability is the main factor controlling methanotrophs' activity. The high-affinity CH_4 oxidation occurs at a low CH_4 concentration (<12 ppm) close to that of the atmosphere (Topp and Hanson, 1991). Approximately 10% of total CH_4 consumption is contributed by methanotrophs (Topp and Pattey, 1997). In comparison, low-affinity CH_4 oxidation appears at high CH_4 concentrations (>40 ppm). In flooded rice cropping soils, over 90% of the

Table 2 Annual CH_4 fluxes in a typical mono-rice paddy field under different fertilization

	Total CH_4 flux (kg ha^1)		
Treatment	Rice cropping	Fallow	Total
Chemical fertilizer (NPK)[a]	220	−1.6	218
Green manure[b]	904	22.7	881

[a] Chemical fertilization: $N\text{-}P_2O_5\text{-}K_2O$ = 90-45-57 kg ha^1.

[b] The mixture of barley and hairy vetch was cultivated during the cold fallow season, and its whole biomass (8.4 Mg ha^1 on dry weight) was applied for rice cultivation.

CH_4 formed may be reoxidized by methanotrophs in aerobic soil areas (Sass et al., 1990; Frenzel et al., 1992; Oremland and Culbertson, 1992). Methane oxidation in the rhizosphere most strongly influences net CH_4 flux but varies according to rice growth stage (Van der Gon and Neue, 1996). Methanotrophs' activity and root oxidation activity show a highly positive correlation (King et al., 1990).

Most of CH_4 is emitted through the rice aerenchyma channel to the atmosphere, but a small portion of CH_4 is emitted as bubbles from soils via ebullition and diffusion. Rice plants' aerenchyma acts as a chimney, allowing for gaseous CH_4 exchange from soil to the atmosphere (Neue and Roger, 1994). Paddy fields with rice plants generally emit more CH_4 than flooded paddy fields without plants, due to easier transfer to the atmosphere and higher organic substrate availability for methanogenesis (Schütz et al., 1989).

Methane passively transfers from soils to the atmosphere (Nouchi et al., 1994). The CH_4 fluxes vary with rice varieties, mainly due to differences in root exudate production, oxidation potential, and morphological characteristics (Adhya et al., 1994; Butterbach-Bahl et al., 1997; Gutierrez et al., 2013). At the early rice-growing stage, CH_4 is emitted through a vertical movement of gas bubbles in the soil, but the diffusion through the aerenchyma becomes the dominant CH_4 transport pathway as plants grow. At the rice reproductive stage, over 90% of CH_4 is transported via the aerenchyma channel (Cicerone and Shetter, 1981; Schütz et al., 1989; Tyler et al., 1997).

4 Nitrous oxide emissions in rice paddy soils

The impact of N_2O emission from rice paddies on net GWP was found to be negligible. IPCC (Klein et al., 2006) proposed 0.003 kg N_2O-N kg^1 N as the emission factor of N_2O for flooded rice fields. Nitrous oxide formation is influenced by many factors including soil redox, available N and OM, but N_2O is principally produced via microbial denitrification and nitrification (Butterbach-Bahl et al., 2013; Shakoor et al., 2021; Thilakarathna and Hernandez-Ramirez, 2021).

In flooded rice paddies, soil redox conditions are not ideal for biological N_2O formation. Water drainage for mitigating CH_4 formation does not lead to high amounts of N_2O formation (Hou et al., 2000; Johnson-Beebout et al., 2009). More intermittent flooding or midseason drainage can lead to higher nitrification and denitrification rates and consequently increase N_2O emissions (Harrison-Kirk et al., 2013; Lagomarsino et al., 2016; Liang et al., 2016). However, intermittent irrigation over five cycles increased seasonal N_2O fluxes by only three times over continuous flooding of rice fields (Kritee et al., 2018), but the GWP of these fluxes is much lower than CH_4 fluxes.

5 Evaluation of the net global warming potential and greenhouse gas intensity of rice paddy soils

Since paddy rice soils can be a GHG source and sink, the effect of agricultural management practices on global warming should be measured by net GWP. This can be done through the integration of two GHG fluxes (CH_4 and N_2O) and SOC stock changes measured in CO_2 equivalents (Mosier et al., 2006). The closed static chamber method is broadly utilized to estimate CH_4 and N_2O fluxes in paddy rice soil (Fig. 3) (Schütz and Seiler, 1989). Diffusive GHG fluxes are directly quantified using the change of gas concentrations over short time intervals multiplied by the chamber volume (m^3) per area (m^2) ratio (Rolston, 1986). Because rice plants significantly influence CH_4 production, oxidation, and emission dynamics, the rice seedling inside the chamber should be properly planted to reflect the way that they experience representative growth conditions in rice fields. To calculate net GWP (Eq. 1), SOC stock change (ΔSOC) should be properly estimated along with CH_4 and N_2O fluxes. The yield scaled GHG emission impact can be compared using GHGI (kg CO_2-eq. Mg^{1} grain) that indicates the net GWP (kg CO_2-eq. ha^{1}) per grain yield (Mg ha^{1}) (Li et al., 2006; Weller et al., 2016):

$$\text{Net GWP} = \text{CH}_4\ \text{flux} \times 25 + \text{N}_2\text{O flux} \times 298 - \Delta\text{SOC} \times 44/12 \tag{1}$$

SOC stock changes are conventionally used to estimate CO_2 exchange in arable lands. However, this practice is not precise enough to represent short-term SOC stock changes, mainly because of the big background pool and large spatial variation of SOC contents (Ciais et al., 2010; Conant et al., 2011; Smith et al., 2020). Theoretically, SOC change can be estimated using net ecosystem C budget (NECB) representing the balance between C input and output under

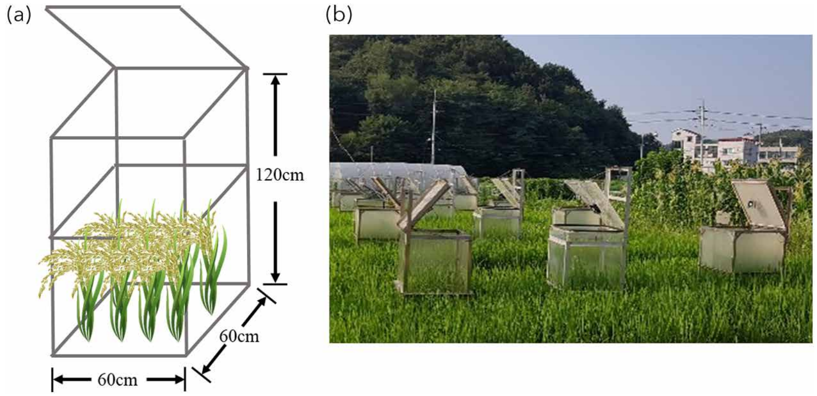

Figure 3 Installation of the closed static chamber to determine CH_4 and N_2O flux during rice cultivation.

the limited system boundary (Smith et al., 2010; Jia et al., 2012; Ma et al., 2013). For example, in rice paddies, the C input source includes the net primary production (NPP) of rice and weeds, organic amendments, fertilizers, etc. In comparison, the C output source includes harvest C removal and heterotrophic respiration (CO_2-C and CH_4-C fluxes) (Eq. 2). NPP implies total C uptake by plant biomass via photosynthesis. Organic amendments lead to the C addition via organic materials. Harvest C removal means the removed C via crop plant harvesting. Respired C loss indicates heterotrophically respired C losses (CO_2 and CH_4 fluxes) from soils:

$$\text{NECB} = \sum \text{C input} - \sum \text{C output} \tag{2}$$

The NPP (kg C ha^{1}) of rice and weeds can be quantified by their C uptakes (Smith et al., 2010) (Eq. 3).

$$\text{NPP} = \text{NPP}_{\text{above ground}} + \text{NPP}_{\text{root}} + \text{NPP}_{\text{litter}} + \text{NPP}_{\text{rhizo deposit}} \tag{3}$$

The NPP of aboveground biomass can be calculated using biomass productivity and its C content. The NPP of root biomass is calculated as 10% of the NPP of aboveground biomass (Huang et al., 2013). The NPP of litter accounts for the average 5% of whole biomass's NPP (Kimura et al., 2004). Rhizosphere-deposited NPP is estimated to range within 7–15% of total biomass's NPP (Mandal et al., 2008).

6 Effect of water management on global warming potential of rice paddy soils

Since CH_4 is biologically produced by methanogens under strongly anaerobic soil conditions, water-management techniques (i.e. midseason drainage and intermittent irrigation) are expected to be the most promising measure to suppress CH_4 fluxes in flooded rice cropping fields (Yagi et al., 1997). For instance, midseason drainage decreased total CH_4 flux by around 50% in a Japanese rice field (Kimura et al., 1992). To minimize the negative effects of soil flooding and reduction in rice growth and development (i.e. sulfide toxicity and excess tillering, Kanno et al., 1997), short-term floodwater drainage is commonly used in rice cropping regions. However, water drainage during rice cultivation also increases microbial activity, which can increase N_2O emission and microbial respiration (CO_2 emission) (Miyata et al., 2000).

Similar results were obtained in our 2-year field study in South Korea (Haque et al., 2016), where single midseason drainage practice for 3 weeks during the high CH_4 emission period considerably increased soil redox (E_h value) (Table 3). During paddy rice cultivation under continuous flooding conditions, the soil C stock (NECB) was increased by around 3.0 Mg ha^{1} year^{1},

Table 3 Changes of GHG fluxes, soil C stock, and rice productivity by midseason drainage under chemical fertilization (NPK) during rice cultivation

	Seasonal flux (kg CO_2-eq. ha^1)					
Irrigation system	CH_4	N_2O	ΔSOC	Net GWP	Grain yield (kg ha^1)	GHGI (kg CO_2-eq. kg^1 grain)
Continuous flooding	6438	145	3012	3570	6650	0.54
Midseason drainage	3313	185	1775	1723	6650	0.26
Statistical analysis	***	***	***	***	ns	***

Note: Data was modified from Haque et al. (2016).
ns and *** denote not significant and significance at 0.1% level, respectively.

but one single midseason drainage decreased this C stock by around 60%. Midseason drainage also increased seasonal N_2O flux by approximately 30% over that in the continuous flooding conditions (Table 3).

However, to evaluate the net effect of water management on global warming, the trade-off between GHG (CH_4 and N_2O) emissions and soil C stock change must be assessed. A trade-off between GHG emissions and soil C stock changes is frequently reported in rice cropping systems changing from continuous flooding to midseason drainage or intermittent irrigation (Cai et al., 1997, 1999; Yagi et al., 1997; Zheng et al., 2000; Zou et al., 2005). Despite increased SOC loss and N_2O emissions, our single midseason drainage considerably decreased the net GWP value by around 50% over that of continuous flooding, mostly due to a big suppression of CH_4 fluxes.

In addition, the midseason drainage did not influence rice growth and yield properties (Table 3). As a result, the single midseason drainage for 3 weeks can reduce GHGI by approximately 50% over continuous flooding. Such practice may be beneficial for the GWP of rice systems, because rice plants require plenty of water during their root development stage, whereas flooding may not be required at the other growth stages (Minamikawa and Sakai, 2005). Therefore, midseason drainage might be a very useful water management practice to mitigate the impact of GHG emissions without rice productivity changes.

7 Effect of green manure management on global warming potential of rice paddy soils

In rice paddy fields, cover crop cultivation during the fallow season and its biomass recycling as green manure (GM) for rice cultivation is broadly recommended to improve soil quality via SOC stock increase and to replace chemical fertilizers (Garcia-Franco et al., 2015; Yao et al., 2019). In temperate mono-rice cropping paddies like Korea and Japan, winter cover crops (i.e. hairy vetch and Chinese milk vetch as a leguminous crop, rye, barley, and wheat as nonleguminous crops) are cultivated during the cold fallow season, and their biomass as GM is incorporated before rice transplanting.

In general, cover crop biomass productivity determines nutrient accumulation under the same management (i.e. cultivar selection, growing stage, fertilization, water management, etc.) and then directly affects subsequent crop (rice) productivity and its NPP as the main C sink (Hwang et al., 2015). Recently, the mixing cultivation of leguminous and nonleguminous cover crops has been recommended to improve biomass and nutrient accumulation. For example, the mixed seeding of barley and hairy vetch significantly increased cover crop biomass and their nutrient contents compared to those of hairy vetch or barley monocultures (Table 4) (Hwang et al., 2015). The increased biomass productivity accumulated enough nutrients to fulfill the recommended fertilization level (N-P_2O_5-K_2O = 90-45-57 kg ha^1, RDA, 2017) for rice cultivation, and significantly increased rice productivity without chemical fertilization.

However, fresh biomass application also provides large amounts of readily available organic C substrates for methanogens and thus strongly increases CH_4 emission in flooded rice fields (Conrad, 2007; Yang et al., 2010; Li et al., 2013; Kim et al., 2015; Hwang et al., 2017; Lee et al., 2020b; Song et al., 2021). Cover crop biomass incorporation increased the annual CH_4 flux by 2.6–4.2 times over that of chemical fertilization within the rice cropping boundary (Table 5).

Compared with CH_4 flux in a rice paddy, very small N_2O fluxes were detected during the rice cultivation period. Compared with chemical fertilization (NPK), seasonal N_2O flux was not increased by GM application, even though its flux was significantly affected by cover crop species choice (Table 5). Low N_2O emissions were observed when barley with a high C/N ratio was used as a cover crop, whereas seasonal N_2O flux was significantly increased when hairy vetch

Table 4 Effect of mixed seeding of hairy vetch and barley on biomass and nutrient productivities

Seeding ratio (%)		Biomass yield (Mg ha^1, dry weight)			Nutrient accumulation (kg ha^1)			
Hairy vetch	Barley	Hairy vetch	Barley	Sum	C	N	P_2O_5	K_2O
100	0	4.80	0	4.80	1983	110	53	101
75	25	5.79	1.27	7.06	2933	143	72	142
50	50	4.92	2.32	7.24	3020	132	68	140
25	**75**	4.56	3.30	7.86	3287	132	70	149
0	100	0	5.89	5.89	2501	50	36	94
Statistical analysis		***	***	***	***	***	***	***

Note: Data was modified from Hwang et al. (2015).
*** denotes significance at the 0.1% level.

Table 5 Changes in GHG fluxes and rice productivity under different fertilization regimes

Fertilization	Annual flux (Mg CO$_2$-eq. ha^1) CH$_4$	N$_2$O	ΔSOC	Net GWP	Grain yield (Mg ha^1)	GHGI (Mg CO$_2$-eq. Mg^1 grain)
Chemical fertilizer	5.5	3.0	−2.1	10.6	6.7	1.6
Green manure						
Barley	14.4	1.5	5.3	10.6	6.2	1.7
Hairy vetch	15.8	3.5	−0.2	19.5	7.1	2.7
Mixture	23.2	3.4	8.8	17.8	8.1	2.2
Statistical analysis	***	**	**	**	**	***

Note: Data was modified from Hwang et al. (2017).
** and *** denote significance at the 1% and 0.1% levels, respectively.

with a low C/N ratio was used as a cover crop. Whilst chemical fertilization alone slightly decreased SOC stock, biomass application with a high C/N ratio (barley, and a mixture of barley and hairy vetch) significantly increased SOC stock. As far as GWP is considered, cover cropping and its biomass application as GM significantly increased net GWP by around 60–80% compared to chemical fertilization (NPK).

Interestingly, short-term aerobic predigestion of biomass applied to soils before irrigation strongly reduced CH$_4$ emission during rice cultivation (Table 6) (Lee et al., 2020b; Song et al., 2021). Since the same biomass was applied at different time intervals before irrigation for rice cultivation, aerobic decomposition of labile organic C substrates under dried soil conditions might effectively mitigate CH$_4$ emission during flooded rice cultivation. Only 10 days of aerobic predigestion of cover crop biomass incorporated in soils decreased seasonal CH$_4$ flux by 55–60% as compared to flooding without aerobic predigestion (0 days). This mitigation effect was significantly increased with longer aerobic periods. Moreover, short-term aerobic predigestion of biomass applied soils before irrigation did not influence seasonal N$_2$O fluxes.

Short-term aerobic predigestion of GM-amended soils did not influence seasonal SOC stock changes estimated by NECB analysis (Table 6). The same volumes of cover crop biomass were amended as the C input source, and the rice plant's NPP did not change. As a C output source, rice harvest C removal was not affected by aerobic predigestion. The respired C loss thus worked as the main determinant of the NECB scale. In aerobic predigestion plots, high C output through CO$_2$ emission was observed, but the CH$_4$-C flux was decreased, resulting in no statistical differences of total respired-C loss among different aerobic predigestion treatments.

In addition, short-term aerobic predigestion in soils with cover crop biomass effectively decreased net GWP, but was not significantly affected by

Table 6 Effect of aerobic predigestion of biomass amended soils on GHG fluxes and rice productivity

Days before flooding	Seasonal flux (Mg CO_2-eq. ha^{1})				Grain yield (Mg ha^{1})	GHGI (Mg CO_2-eq. Mg^{1} grain)
	CH_4	N_2O	ΔSOC	Net GWP		
30	8.6	2.8	10.9	0.4	5.7	0.1
20	13.6	3.0	10.9	5.6	5.8	1.0
10	18.1	3.4	10.4	11.1	5.8	1.9
0	43.4	2.4	10.1	35.7	5.9	6.1
Statistical analysis	***	ns	ns	***	ns	***

Note: Data was modified from Song et al. (2021).
ns and *** denote not significant and significance at the 0.1% level, respectively.

the duration of aerobic predigestion (10–30 days) before flooding. We found that aerobic predigestion of cover crop biomass over 10 days considerably decreased GHGI by 65–98% as compared to the cover crop treatment without aerobic predigestion (Song et al., 2021). As a result, in GM-amended rice paddies, aerobic predigestion before flooding may be essential to reduce net GWP and GHGI.

8 Effect of straw management on global warming potential of rice paddy soils

Straw recycling is regarded as the most effective management practice to increase SOC stock in rice fields. However, most straw has been removed for livestock feeding and burnt for site preparation, thereby depleting SOC stocks (Wang et al., 2015a; Xia et al., 2018). In Korean rice paddies, straw application level officially decreased from 3.7 Mg ha^{-1} in 1992 to 1.1 Mg ha^{-1} in 1998 (Kim et al., 2003), which consequently resulted in depletion of SOM contents in nationwide rice paddies from the average of 26 g kg^{-1} in the 1960s to 24 g kg^{-1} in the 2000s (RDA, 2010).

In soil C balance (NECB) analysis in a typical rice paddy (Lee et al., 2020a), only chemical fertilization (NPK) without straw return decreased SOC stock by 0.24–1.12 Mg C ha^{-1} year^{-1}. This was caused by harvest C removal (65–73% of total C output) and the respired C loss (27–35% of total C output). However, straw retention as an organic amendment considerably increased SOC stocks by 1.48–2.82 Mg C ha^{-1} year^{-1}. Straw spreading over the soil surface was more efficient than straw incorporation to increase SOC stocks, due to favorable microbial decomposition of incorporated rice straw during the dried fallow season. Moreover, straw incorporation significantly increased CH_4 fluxes during flooded rice cropping. Its addition also increased N_2O emissions, but this

Table 7 Characteristics of GHG emissions and rice productivity under different rice straw management strategies

		Annual flux (Mg CO_2-eq. ha^1)					
Fertilizer management	Straw application	CH_4	N_2O	ΔSOC	Net GWP	Grain yield (Mg ha^1)	GHGI (Mg CO_2-eq. Mg^1 grain)
NPK		6.4	0.9	−2.5	9.8	5.1	1.9
NPK + straw	Mixing	10.2	1.6	7.1	4.8	6.0	0.8
	Spreading	17.8	1.3	8.8	10.4	5.7	1.8
Statistical analysis		***	**	***	**	**	*

Note: Data was modified from Lee et al. (2020a).
*, ** and *** denote significance at the 5%, 1%, and 0.1% levels, respectively.

enhanced flux was still too small to influence the net GWP. SOC stock increase via straw recycling may conflict with CH_4 flux increase in a rice paddy (Hsu et al., 2009), and both fluxes must be considered to evaluate net GWP in rice paddies (see above; Table 7).

In the conventional rice cropping system in which straw is removed and chemical fertilizer is applied, CH_4 flux and SOC stock change represent approximately 65% and 25% of the annual net GWP (average 9.8 Mg CO_2-eq. ha^{-1}), respectively. However, straw retention did not only increase CH_4 flux but also SOC accumulation. In contrast to the general assumption that organic amendments in rice fields significantly increase GHG fluxes and global warming impact (Le Mer and Roger, 2001), rice straw incorporation into soil and aerobic decomposition during the dried fallow season were very effective in decreasing net GWP by around 50% over NPK, primarily due to SOC stock increase. In addition, rice straw addition stimulated rice growth and increased rice grain productivity by 10–20% as compared to paddies managed with straw removal. In contrast, although straw spreading over the surface layer and aerobic decomposition during the long fallow season was effective as a way to increase SOC stocks, it also strongly increased CH_4 emissions. As a result, this kind of straw management was not effective in decreasing net GWP.

In conclusion, straw recycling may be essential to improve soil productivity through SOC stock increase without an equivalent increase in GHG emission impact. However, straw should be incorporated into the mineral soil, not spread over soil surface, to be aerobically decomposed during the long fallow season.

9 Effect of fertilizer management on global warming potential of rice paddy soils

Intensive cropping systems may increase crop productivity but have a negative environmental impact. Of all rice management practices, appropriate fertilization is one of the most effective ways to improve crop productivity and quality. Proper fertilizer management can improve rice plants' photosynthetic capacity, resistance to biotic stress, nutrient uptake, and productivity. For example, in a long-term fertilized rice paddy in Korea, N fertilizer application enhanced rice grain productivity by an average of 45%, which was much higher than 9.8% and 5.1% of grain yield increase by phosphorus (P) and potassium (K) fertilization, respectively (Lee et al., 2008).

However, high N fertilization exceeding plant requirements can decrease N use efficiency (NUE) (Peng et al., 2006; Liu et al., 2015) as well as cause resource loss and environmental pollution. Appropriate N fertilization is important to improve crop productivity and sustain high environmental quality (Tilman et al., 2002; Yousaf et al., 2014). Furthermore, N fertilizer application may increase GHG fluxes from soils (Schimel, 2000; Ma et al., 2007; Liu et al., 2015; Yang et al., 2015). Generally, the N fertilization level shows a highly positive relationship with N_2O emission levels (Ma et al., 2013), because it provides the substrate necessary for biological N_2O formation through nitrification and denitrification (Paul et al., 1993).

There were many contrasting findings related to the influence of N fertilization on CH_4 fluxes in rice paddies (Bodelier et al., 2000; Shrestha et al., 2010; Kim et al., 2019). In several studies (Xie et al., 2010; Dong et al., 2011; Yao et al., 2012), N fertilization considerably decreased CH_4 fluxes, mostly because of enhanced CH_4 oxidation in the rice rhizosphere. However, in many other cases, N fertilization strongly increased CH_4 formation and emissions, due to stimulation of methanogen activity (Schimel, 2000; Cai et al., 2007). In our 2-year field study (Kim et al., 2019), N fertilization significantly increased seasonal N_2O fluxes (Table 8). Moreover, seasonal CH_4 fluxes also increased with N fertilization increase, peaking at around 130 kg N ha^{-1} of urea addition and thereafter decreased. Consequently, N fertilization has a considerable

Table 8 Characteristics of GHG emissions and rice productivity under different N application levels

	Annual flux (Mg CO_2-eq. ha^1)					
N application (kg N ha^1)	CH_4	N_2O	ΔSOC	Net GWP	Grain yield (Mg ha^1)	GHGI (Mg CO_2-eq. Mg^1 grain)
0	6.2	0.17	−5.0	11.3	4.6	2.5
45	6.6	0.23	−4.8	11.7	5.6	2.1
90	7.4	0.27	−4.6	12.2	6.8	1.8
180	7.1	0.33	−4.7	12.2	5.9	2.1
Statistical analysis	*	***	***	**	**	*

Note: Data was modified from Kim et al. (2019).
*, ** and *** denote significance at the 5%, 1%, and 0.1% levels, respectively.

effect on GWP, but in contrast to what may be expected, net GWP was mostly influenced by the CH_4 flux, which represents more than 90% of the total GWP.

Similar to changes in GWP, GHGI is increased by N addition (Kim et al., 2019). In a typical Korean rice paddy, the lowest GHGI was observed at 104–112 kg N ha^{-1} of urea application, and thereafter, the GHGI was increased with N fertilization increase, mainly due to a decrease in grain productivity at high N fertilization. Theoretically, any soil management practice that can decrease N fertilization levels without changing crop productivity will result in the lowest GHGI (Mosier et al., 2006). Consequently, N fertilization should be carefully managed to achieve sustainable rice cultivation systems with high rice productivity and low GWP and GHGI.

10 Effect of soil amendments on global warming potential of rice paddy soils

Methane is produced through the anaerobic decomposition of organic substrates when CO_2 is used as an electron acceptor. Soil microorganisms, which can reduce energetically more favorable electron acceptors (i.e. O_2, NO_3^-, Mn^{4+}, Fe^{3+}, SO_4^{2-}) may outcompete methanogens using the less favorable electron acceptor (i.e. CO_2) (Lovley et al., 2004). Methanogenesis may thus be suppressed by adding alternative electron acceptors to extremely reduced soils. This suppression might result in a combination of inhibition and competition effects for common electron donors (Achtnich et al., 1995; Jakobsen et al., 1981).

Soil amendments that contain electron acceptors (i.e. ammonium nitrate, ammonium sulfate, iron slag-based amendments, etc.) can be utilized to mitigate CH_4 production in flooded rice fields. For example, iron oxide (Fe_2O_3) can react as an important oxidizing agent and control the formation of organic acids (Asami and Takai, 1970) and CH_4 (Watanabe and Kimura, 1999) in anaerobic soils.

For example, blast furnace slag (BFS, also known as iron slag) based silicate fertilizer contains around 4.8–5.4% and 0.3–1.1% of Fe and Mn oxides, respectively (Ali et al., 2009a; Lim et al., 2021). In Korean and Japanese rice paddies, silicate fertilizers have been used as alkaline amendments to improve acidic soil pH and provide valuable elements for rice over 50–100 years (Datnoff et al., 1997). During rice cultivation, silicate fertilization strongly increases dissolved Fe contents in soils (Ali et al., 2008a; Wang et al., 2015b), which suppresses methanogens` activity and CH_4 emissions.

Moreover, the addition of silicate fertilizer stimulates rice root activities (Zhang et al., 2020). The solubility of Fe and Mn oxides can be expected as the anaerobic condition continues to develop (Gotoh and Patrick Jr, 1974; Miao et al., 2006). Rice roots emit a high amount of O_2 to reduce Fe and Mn toxicity, thus decreasing their solubility (Mei et al., 2012), as the solubility of oxidized

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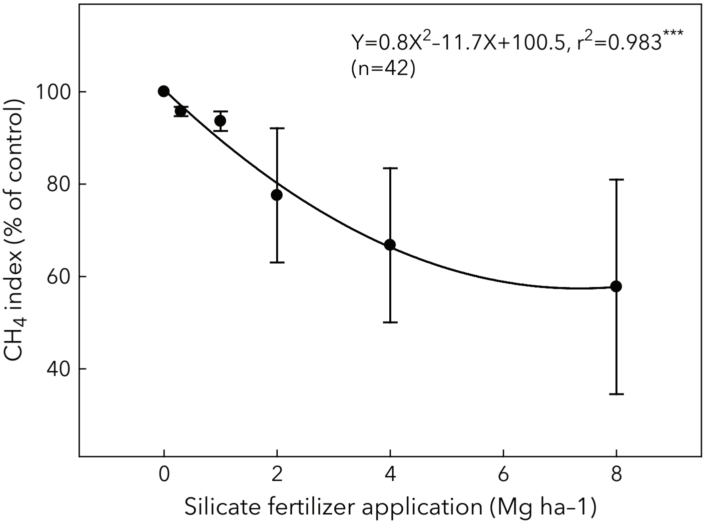

Figure 4 Changes of CH_4 flux index (% of control) under different levels of silicate fertilizer (blast furnace slag) application as soil amendment in rice paddies (Lim et al., 2021).

Fe and Mn is much lower than those of the reduced Fe and Mn compounds (Schwertmann, 1991). Hence, CH_4 inside the rice rhizosphere can be indirectly oxidized by methanotrophic bacteria. Therefore, silicate fertilizer application was effective in suppressing CH_4 emission during rice cultivation, probably due to the added Fe^{3+} and Mn^{4+} as an electron acceptor and the improved oxidation potential in rice roots (Liang et al., 2007; Ali et al., 2008a,b; Ali et al., 2009a,b; Lee et al., 2012; Das et al., 2020). By analyzing data from several studies, Lim et al. (2021) showed that the CH_4 flux index (%), which is used to compare the total CH_4 flux from blast furnace slag treated plots to that of control plots, considerably decreased as the fertilization increased (Fig. 4).

Silicate fertilizers have alkaline pH and contain high amounts of calcium oxide (CaO) and silicate (SiO_2) as their main components (Proctor et al., 2000; Gwon et al., 2018; Lim et al., 2021). In irrigated paddy fields, rice accumulates SiO_2 by around 10% of the total biomass on dry weight (Savant et al., 1996; Ma et al., 2006). Silicate fertilizer enhances rice plant erectness and reduces lodging damage (Idris et al., 1975; Hossain et al., 2002). This improvement in rice plants' physical properties increased rice productivity and improved rice quality. Rice grain productivity may be maximized at around 4 Mg ha^{-1} of silicate fertilizer application with an average of 18% increase (Lim et al., 2021). Therefore, application of soil amendments containing electron acceptors and silicate can be an effective soil management strategy to reduce CH_4 emission in rice fields and concomitantly increase rice productivity via improvement of soil properties.

11 Effect of biochar and compost addition on global warming potential of rice paddy soils

To simultaneously increase SOC stocks and decrease CH_4 emission in rice fields, the utilization of stabilized organic amendments (i.e. biochar and compost) has been recommended (Woolf et al., 2010; Feng et al., 2012; Weng et al., 2017: Qi et al., 2018; Jeong et al., 2019). However, in most studies, the effect of stabilized organic amendment applications on GHG fluxes and SOC stock changes was evaluated only within the cropping system but did not consider additional GHG fluxes from industrial processes when producing biochar and compost (Zhong et al., 2013; Jeong et al., 2018). It is largely unknown if biochar and compost amendments in rice soils can fully reduce GHG emission impacts within the whole process from their production to land utilization.

To assess the impact of organic amendment applications on GHG emissions (taking into account their production and application) (Canatoy et al., 2022), three different types of swine manure (fresh, compost, and biochar) were selected for comparison. Air-dried swine manure was mixed with sawdust (50% of dried weight) and used to make compost and biochar. To make biochar, the manure mixture was pyrolyzed at 400°C for 4 h. To investigate GHG fluxes in rice cropping systems, the three different types of organic amendments (fresh, compost, and biochar manure) treatments were applied with the same rate (12 Mg ha^1 on dry weight) under the same fertilization and managements. The whole system analysis was divided into industrial and cropping processes. During the industrial process, to produce compost and biochar, direct GHG fluxes were evaluated by the closed chamber method. Additional GHG fluxes from transportation and electricity consumption were taken into consideration by using European Emission Standards 3 and 4 (European Parliament Council, 2000). In the rice cropping process, biogenic GHG (CH_4 and N_2O) fluxes were directly monitored using the closed chamber method, and SOC stock changes were evaluated by analyzing the NECB which means the difference between C input and output (Smith et al., 2010).

In comparison with fresh manure, compost showed a high potential to increase SOC stocks and reduce CH_4 fluxes after soil application. Although compost application reduced net GWP by around 43% over fresh manure, it also showed huge GHG emissions, amounting to 25.8 Mg CO_2-eq ha^1 of net GWP. Biochar was much more effective than compost in decreasing net GWP in a rice paddy, via strong reduction in CH_4 emissions and a high increase in SOC stocks (Agegnehu et al., 2016; Phuong et al., 2020). Biochar amendment resulted in favorable environmental conditions for methanotrophic proteobacteria to proliferate, which resulted in an enhanced rate of CH_4 oxidation (Feng et al., 2012). Moreover, biochar functionally reduced N_2O as it aged in the soil due to an enhanced sorption of nitrate and ammonium via oxidative reactions on its

Table 9 Life cycle analysis to evaluate GWP and GHGI under different types of manure amendments

			Biochar manure		
System boundary	Fresh manure	Compost manure	Without syngas recycling	With syngas recycling	Statistical analysis
Industrial process (Mg CO_2-eq. ha^1)					
Net GWP	0.07	34.5	32.6	13.5	
Cropping process (Mg CO_2-eq. ha^1)					
CH_4 flux	54.9	40.9	17.9	17.9	***
N_2O flux	2.2	1.7	1.1	1.1	**
ΔSOC	12.1	16.8	19.0	19.0	**
Net GWP	45.0	25.8	−0.12	−0.12	**
Whole process					
Net GWP (Mg CO_2-eq. ha^1)	45.1	60.3	32.5	13.4	**
Grain yield (Mg ha^1)	7.8	8.4	8.2	8.2	**
GHGI (Mg CO_2-eq. Mg^1 grain)	5.8	7.1	3.9	1.6	***

Note: Data was modified from Canatoy et al. (2022) (under revision in *Science of the Total Environment*). ** and *** denote significance at the 1% and 0.1% levels, respectively.

surfaces (Singh et al., 2010). SOC stocks increased under biochar addition by around 57% and 13% over fresh manure and compost, respectively. As a result, biochar application converted rice paddy into a GHG sink with minus 119 kg CO_2-eq. ha^1 of net GWP. Similar results were reported in several rice cropping studies (Liu et al., 2016; Mohammadi et al., 2020).

In the industrial process (compost and biochar production and transport processes), large amounts of GHGs were emitted (Table 9). Composting takes place under aerobic conditions, which lead to decomposition of labile organic substrates, resulting in their transformation into a more stabilized form via enzymatic biochemical degradation, releasing mainly CO_2 during the conversion process (Fukumoto et al., 2003; Mehta et al., 2014). In our study, a total of 34.3 Mg CO_2–eq. of biogenic GHGs were released to make 12 Mg of compost from 24.2 Mg of manure mixture. This net GWP consisted of nearly 55%, 37%, and 8% of CO_2, N_2O, and CH_4 fluxes, respectively. Although CO_2 is an intrinsic byproduct of composting not accounted for by IPCC calculations, it is still important for implementing abatement technologies to reduce global warming (Sánchez et al., 2015). Without gas capturing facilities during the compost production process, these levels of GHGs could markedly influence global warming and, therefore, overall GHG emissions should be carefully considered in evaluating the effect of compost utilization on GHG emissions in paddy fields.

In our study, without a syngas recycling system during the pyrolysis process, a total of 19.2 Mg CO_2–eq. syngas GHGs were emitted to make 12 Mg of biochar from 24.8 Mg of manure mixture (Table 9). This net GWP consisted of around 66% and 34% of CO_2 and CH_4 fluxes, respectively. However, the use of a syngas recycling system was reported to impede CO_2 and CH_4 formation and further convert them into non-GHGs like CO, H_2, and water (Shen et al., 2017; You et al., 2018; Schmidt et al., 2019). Conversely, N_2O emission during pyrolysis negligibly influenced net GWP of the industrial process (Pennise et al., 2001; Clark et al., 2017). As a result, pyrolysis with syngas recycling can reduce this net GWP by 59% over a no syngas recycling system.

Considering the whole life cycle from industrial to rice cropping processes, compost utilization as organic amendment significantly increased net GWP compared to fresh manure and biochar treatment, due to huge amounts of biogenic GHG emissions during the composting process. In comparison with fresh manure, compost application was very effective in reducing GHG emission impact during the rice cropping process (Islam et al., 2020), but the additional GHG fluxes from composting process markedly increased net GWP within the life cycle analysis (Table 9). In the biochar treatment, although similar levels (32.6 Mg CO_2-eq.) of GHGs were released during pyrolysis with the composting process, the longevity of biochar after soil application and the use of syngas recycling system may have positive effects on decreasing GWP. Hence, when the whole life cycle is considered, biochar application significantly reduced net GWP by a minimum of 28% and 46% and a maximum of 70% and 78% over fresh manure and compost, respectively. The minimum and maximum reductions were estimated from industrial processes without and with a syngas recycling system, respectively. Irrespective of the syngas recycling system, lifecycle analysis showed that biochar application to rice paddies may convert them into a huge GHG sink.

Compost manure application considerably increased rice grain productivity over fresh manure which might be due to higher available nutrients and improved soil qualities (Sadegh-Zadeh et al., 2018). No statistical difference was noted among the three selected manure treatments, only a trend to higher rice productivity in compost treatments (Table 9). In comparison with fresh manure, compost application significantly increased GHGI, while biochar highly decreased GHGI by 33% and 72% over fresh manure without and with a syngas recycling system, respectively. Therefore, biochar utilization rather than compost as organic amendment could be a promising option to maintain soil quality and suppress GHG emissions in rice cultivation systems.

12 Conclusion

Anaerobic conditions in paddy soils during flooding lead to SOC accumulation but also significantly increase CH_4 emissions, which has a much greater impact than changes in SOC stock or N_2O emissions on GWP of rice cropping systems.

In these systems, agricultural management practices must consider trade-offs in the form of CH_4 emissions, which could outweigh SOC sequestration.

The combined management of aerobic decomposition of rice straw or predigestion of organic amendments before flooding and irrigation of water drainage during rice cropping can significantly decrease net GWP over conventional soil management. In addition, careful management of fertilizers and utilization of soil amendments that have electron acceptors can reduce CH_4 emissions and net GWP, in addition to improving soil productivity. As a stable organic amendment, biochar (rather than compost) is effective to mitigate GHG emission impact and improve soil quality. In conclusion, more stable organic amendments like biochar may be useful to decrease the global warming impact and improve soil quality in irrigated rice fields. The combined management of organic amendments with water and soil amendments, which impede methanogenesis, can also be an important option to mitigate GHG emissions of rice paddies.

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