Chapter 9
Rice Straw Management Effects on Greenhouse Gas Emissions and Mitigation Options

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Abstract Lowland rice is a significant source of anthropogenic greenhouse gas emissions (GHGEs) and the primary source of agricultural emissions for many developing countries in Asia. At the same time, rice soils represent one of the largest global soil organic carbon sinks. Straw management is a key factor in controlling the emissions and mitigation potential of rice primarily by affecting methane (CH_4) from anaerobic decomposition and carbon losses from burning. Achieving climate-smart management of rice while also improving yields and farm profits, however, is challenging due to economic-environmental trade-offs. This balance could be met with appropriate site-specific practices. This chapter discusses these straw management practices that affect yield-scaled GHGEs and mitigation options in different rice environments.

Keywords Greenhouse gas emissions · GHG · Mitigation · Rice straw

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9.1   Introduction

Lowland rice is a major contributor to greenhouse gas emissions (GHGEs) accounting for 10% of global emissions from agriculture (FAO 2015). This number is even higher for Southeast Asia (SEA) where 90% of the world's rice is produced, making up 10–20% of the region's total anthropogenic emissions and 40–60% of its agricultural emissions (UNFCC 2019). Rice is one of the largest sources of anthropogenic CH_4 (GWP[1] = 28) and a major contributor of N_2O (GWP = 265). CO_2 emissions from rice, although large, are considered net-neutral from photosynthesis according to the IPCC 2006 guidelines. CH_4 accounts for around 65% of global CO_2 eq emissions from lowland rice; largely from anaerobic decomposition of straw and crop residue under continuously flooded conditions. The remaining 35% of emissions from rice can be attributed mostly to N_2O from soil N cycling of fertilizer and to a smaller extent N from crop residues (EPA 2013). Rice straw management is, therefore, an important factor in controlling GHGEs from lowland rice-cropping systems.

In addition to emissions, straw management plays an important role in global carbon cycles through soil organic carbon (SOC) sequestration. SOC is an important indicator of soil quality, which suggests its importance in improving farmer adaptation to climate change. It is estimated that rice soils contain the largest SOC stocks among croplands (IPCC 2007; Lal 2004). The potential SOC deposition from returning rice straw to the soil is significant as almost half of the total carbon in rice plant residue is within the straw and stubble (although root C contributes most SOC). The common, yet mostly banned, practice of straw burning reduces the SOC sequestration potential of fresh straw incorporation.

Although returning fresh straw to the field can increase SOC, its sequestration benefits may be outweighed by the increase in CH_4 emissions when applied under flooded conditions due to anaerobic decomposition. Additionally, straw management practices that reduce emissions or improve sequestration are not always advantageous to crop yields. Striking a balance between emissions reduction, carbon sequestration, and crop yields is challenging, but may be achievable with optimal site-specific straw management. The efficiency of this balance can be quantified by yield-scaled emissions and mitigation or NGWP and GHGI,[2] more broadly referred to as climate-smart agriculture (CSA). This chapter discusses in-field/off-field rice straw management options affecting CSA—burning, incorporation, com-

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[1] Global warming potential (GWP) is a measure of how much heat a greenhouse gas traps in the atmosphere up to a specific time horizon, relative to carbon dioxide (CO_2).

[2] Net global warming potential (NGWP) can be defined as the radiative properties of all the GHG emissions plus carbon fixation, expressed as CO_2 eq ha^{-1} year^{-1} (Robertson and Grace 2004), while greenhouse gas intensity (GHGI) defines the GWP per unit of crop yield (Mosier et al. 2006)

posting, biochar, and others—under various rice production environments, such as water management, cropping system, and soil type.

9.2   In-Field Straw Management Effects on Emissions and Mitigation

9.2.1   Burning

Open-field burning of rice straw has well-known negative environmental and agronomic impacts due to atmospheric pollution and reduced soil quality. Burning also emits GHGs CO_2, CH_4, and N_2O, along with other trace gases that contribute to tropospheric ozone and the formation of Atmospheric Brown Cloud (ABC)—a cause of severe human health concern (Arai et al. 1998; Gullett and Touati 2003; Lin et al. 2007; Tipayarom and Kim Oanh 2007; Torigoe et al. 2000; Kanokkanjana et al. 2011). Still, studies suggest that the total GHGEs from burning are up to 98% lower than those from fresh straw incorporation in flooded soils due to reductions in CH_4 from straw decomposition (IPCC 2006). This accounting, however, excludes CO_2 emissions, which are considered net neutral from photosynthesis in the IPCC guidelines. When CO_2 is included, the carbon losses from burning reduce the SOC sequestration potential of fresh straw incorporation due to the immediate 90% loss of straw C as CO_2 during combustion (Chen et al. 2019). When this is accounted for, the NGWP from burning is comparable to that of complete fresh straw incorporation (Lu et al. 2010).

SOC sequestration is thus an important component of emissions calculations from burning. For example, a meta-analysis in China compared the effects of burning and straw incorporation on NGWP to include sequestration and found that switching from burning to straw incorporation could mitigate 34.18 Mt. CO_2 eq $year^{-1}$ or 31% of total rice emissions in the country (Lu 2015; Liu et al. 2014). This assumed a large sequestration potential by restoring degraded soils to their maximum SOC storage ability or SOC saturation capacity (EPA 2013). Once saturation was reached, the mitigation potential of straw incorporation diminished. Increasing SOC not only mitigates emissions, but can also substantially improve soil quality, yields, and adaptation to climate change by improving drought tolerance. For example, an only 1% improvement to SOM can double the soil water holding capacity (Fileccia et al. 2014).

Despite the established negative long-term impacts of burning on soil quality, SOC sequestration and air quality, intensive rice farmers prefer burning rice straw due to lower costs, reduced weed and disease carryover, and ease of tillage. Advantages of burning may decline as opportunities increase for off-farm uses and stricter government environmental regulations encourage alternative options.

9.2.2 Incorporation Rates and Environmental Factors

9.2.2.1 Water Management

CH_4 emissions from rice are highly dependent on the amount of straw or crop residue returned under continuously flooded conditions (Liu et al. 2014). Because of this, removing rice straw in flooded rice is considered a mitigation strategy that could theoretically reduce the GWP of emissions from rice by 45% (Wang et al. 2016). The benefits of complete straw removal on reducing emissions, however, are offset by reduced SOC sequestration, soil quality, and long-term yields. Maximum emission reductions and yield (and SOC deposition) may be best achieved by partial straw return/removal in most continuous rice systems (Romasanta et al. 2017). This balance can still increase SOC storage over time and provide adequate crop nutrients. Because straw decomposition rates, and thus emissions, depend on climate, cropping system, and soil type, these factors can help determine the appropriate percentage of straw to return. Generally, soils that are well-drained or have low SOC with aerobic periods benefit from increased straw return to maximize SOC sequestration and increase yields with minimal CH_4 emissions, i.e., the percentage of straw returned should be approximately proportional to the percentage of time under aerobic conditions (Monteleone et al. 2015).

Controlling the aerobic condition of paddy soil is primarily achieved by irrigation management. The use of non-flooded, aerobic periods to reduce CH_4 from organic matter decomposition in rice is a well-established mitigation strategy called alternate wetting and drying (AWD) that can reduce emissions in lowland irrigated rice by 48% on average (IRRI 2016). AWD will be an increasingly important strategy to mitigate future emissions of CH_4 as expanding combine harvester use promotes straw incorporation. Reduced flooding can also be achieved with the use of laser land-levelling, dry direct-seeded rice, and short-duration rice varieties. These methods are well established water-saving practices described in previous studies (Monteleone et al. 2015; Bouman et al. 2007). Reduced flooding affects emissions by shifting from anaerobic to aerobic microbial respiration to produce CO_2 in place of CH_4. Although CO_2 emissions increase under aerobic conditions, the effect on GWP is much lower than CH_4. Additionally, aerobic decomposition of residue improves SOM conversion to more stabilized forms of SOC that have a lower additive effect on CH_4 once flooded (Jiang et al. 2019).

Despite the benefits of aerobic regimes on emissions from rice straw, it comes with an increased risk of SOC loss compared to continuous flooding. Additionally, N_2O emissions may be significant during dry conditions— although N_2O emissions are largely an effect of fertilizer, as straw supplies only around 10% of N in intensive systems (Yadvinder-Singh et al. 2004; Eagle et al. 2001). In more aerobic rice systems, N_2O emissions can be mitigated by proper nutrient management, and SOC losses can be compensated for by increasing the rate of straw return.

9.2.2.2   Cropping System

As with irrigation management, the type of cropping system is an important factor in controlling soil conditions and emissions from rice straw. Because fallow conditions and upland crops mostly eliminate anaerobic conditions for CH_4 production, the emissions from aerobic decomposition (N_2O, CO_2) and loss in SOC can be significant. For example, SOC levels in a long-term rice–maize rotation at IRRI were 14% lower than that of continuous rice (Witt et al. 2000). For this reason, intensive rice–upland cropping systems may require complete straw return to the upland crop to prevent SOC depletion.

9.2.2.3   Tillage

Tillage type and timing can greatly affect emissions from straw returned to the field. When straw is chopped and incorporated into the soil at least 30 days before flooding, rice CH_4 emissions have been shown to be reduced by up to 80% (Launio et al. 2013; Kajiura et al. 2018). Reduction CH_4 emissions can be attributed to the increased aerobic decomposition of straw to stabilized SOM before flooding. Due to the additional benefits of early incorporation to planting and soil quality, it is considered a CSA priority for flooded rice. In fact, studies show early incorporation is one the most cost-effective, climate-smart rice straw management options (Launio et al. 2016).

When residue is removed, tillage has shown to increase emissions and reduce SOC in rice. A meta-analysis on 48 studies on continuous rice in China showed that no-till reduced the GWP from CO_2 and CH_4 by 20.4% when straw was removed, but had no significant effect when straw was returned (Feng et al. 2018; Huang et al. 2018).

In upland crops after rice, no-tillage with full straw returned is an established CSA strategy for many rice–upland environments (Grace et al. 2012). A study on marginal abatement costs suggest that no-till accounted for 70% of the cost-effective GHG mitigation potential in 2010 across non-rice crops (EPA 2013). The effects of no-till and straw mulching on yield, GHG emissions, and soil quality are most pronounced in rainfed, light textured soils. In fact, no-till for the rice–wheat rotation is credited as one of the greatest resource-saving technologies for the Indo-Gangetic Plains (Erenstein 2009; Zandstra 1982). Tillage is shown to stimulate mineralization and oxidation of SOM in aerobic soils, causing a reduction in SOC and increase in N_2O emissions. These effects have been established in many meta-analyses (Zhao et al. 2015; Feng et al. 2018; Lu 2015; Liu et al. 2014). Therefore, the optimal tillage management for CSA in rice–upland systems is often complete straw returned as mulch with no-till in the upland crop followed by early residue incorporation or removal before flooded rice.

9.2.2.4 Soil Type

Emissions and mitigation from rice straw management are highly dependent on soil type (Badagliacca et al. 2017). A meta-analysis of GHGE studies across Japan showed that CH_4 emissions significantly varied by soil type by as much as 200% (Kajiura et al. 2018). Still, the soil properties that stimulate CH_4 emissions from straw incorporation are not well understood. Conditions known to stimulate methanogenesis are a soil redox potential below -200 mV and neutral pH. It can be assumed that the variability in CH_4 production by soil type may be related to differences in soil nutrients. Some studies suggest that high levels of ammonia and sulfates are known to inhibit methanogenesis (Sánchez et al. 2015).

The ability of straw incorporation to improve SOC sequestration is also affected by soil type. Generally, soils which have been depleted of SOC and contain high clay or oxygen-reduced conditions can store more C. It is estimated that returning crop residues to these soils along with proper CSA management could help sequester enough SOC to offset the current increase in emissions from all anthropogenic sources (White 2017).

9.2.2.5 Fertilizer

Studies suggest there is a significant interaction effect of rice straw management and fertilizer on GHGEs. Yet, the degree of this effect is complex and thus difficult to form conclusions on management recommendations. N_2O emissions from the application of organic and inorganic fertilizers are, however, an important topic as they represent 5% of global anthropogenic emissions (IPCC 2007). Although N_2O is considered negligible during most rice production, which is flooded or kept saturated, trends towards more aerobic rice systems due to water limitations and increasing upland crop rotation make N_2O a concern. A meta-analysis on 112 assessments showed that straw incorporation can reduce N_2O emissions from fertilizer by 27% in rice, although straw incorporation alone generally increased N_2O due to the inherent N content of straw (Shan and Yan 2013). There is also evidence that CH_4 emissions from straw incorporation are affected by fertilizer. A meta-analysis of 155 data pairs showed that N fertilizer stimulated CH_4 emissions in 64% of cases and the stimulatory effect of N fertilizer on CH_4 was two to threefold greater with urea than with ammonium sulphate (Banger et al. 2012).

9.3   Off-Field Straw Management Effects on GHGEs

9.3.1   Composting

Straw composting with manure can be an effective option to reduce CH_4 emissions associated with in-field straw incorporation along with CH_4 and N_2O emissions from manure management. Manure management accounts for 11% of global agricultural emissions, thus is an equally important GHG source as lowland rice. Emissions from manure are mainly in the form of CH_4 from anaerobic settling ponds (23%) and N_2O from manure applied to soils and dry storage (77%) (FAO 2017).

Aerobic composting is an effective method to reduce methanogenesis of CH_4 from anaerobic manure storage in settling ponds. Studies suggest aerated manure with straw can reduce CH_4 emissions up to 90% compared to anaerobic storage (Petersen et al. 2013). The effects of composting on N_2O emissions from manure are, however, more complex than CH_4. N_2O is emitted indirectly from manure mainly by NH_3 volatilization, which converts to N_2O in the atmosphere. Smaller, but additional N losses can occur from NO_3 leaching/erosion, which also convert to N_2O. Improper field application of manure or composting can cause an almost 100% loss of manure N to the atmosphere affecting both GHGEs and N supply value if used for fertilizer. This often occurs when manure is applied to soils with high pH and low CEC, and without injection/incorporation. In this scenario, composting manure with rice straw could provide substantial emissions mitigation.

Rice straw is an ideal bulking agent for manure compost due to its high C:N ratio, which can help maintain the ideal 25:1 of the compost. This C:N ratio maximizes N immobilization and substrate adsorption, which minimizes losses by volatilization and leaching. N losses from proper composting may be as low as 13% of the original feedstock N (Chadwick et al. 2011). The opportunity to mitigate N_2O from composting, however, may be fairly small given many farms can avoid 100% N loss by injecting/incorporating manure or applying it directly to soils with high CEC, clay, or low pH. In this case, the mitigation opportunity of straw/manure compost may be primarily through avoiding CH_4 emissions from anaerobic manure storage and in-field rice straw incorporation, along with the potential indirect abatement of emissions from N fertilizer production (Chen et al. 2011). An additional, yet understudied, effect of rice straw composting vs. in-field incorporation may come from increased SOC sequestration. Although studies are limited, some suggest composting increases the stabilized fraction of SOC and sequesters more carbon compared to in-field aerobic decomposition of residue (Spaccini and Piccolo 2017).

The added step of producing mushrooms from straw compost could theoretically reduce N_2O emissions further by increasing N immobilization through mushroom nutrient uptake, although this has not been established. Studies do suggest that in-field emissions of CH_4 can be substantially mitigated by incorporating spent mushroom compost to the field in place of fresh rice straw. One study in the Philippines estimated CH_4 emissions from mushroom production at only 73 g CH_4 t^{-1} of straw (dry weight) compared to the IPCC default emission factor of 4 kg CH_4 t^{-1} for straw manure compost (Truc 2011). Arai et al. (2015) also found that the total GWP in straw-mushroom cultivation is 12.5% lower than straw burning.

9.3.2 Biochar

Like compost, biochar can mitigate the CH_4 emissions associated with fresh straw incorporation by providing an off-field use for straw. The total mitigation potential of biochar, however, extends beyond compost due to its ability to improve sequestration by converting straw to a more stabilized form of C (Yin et al. 2014). Studies on C cycling of crop residue suggest that incorporation and composting lose 80–90% of the initial carbon as CO_2 during decomposition in the first 5–10 years. In contrast, about 50% of the carbon can be captured as stable SOC when residue is converted to biochar (Lehmann et al. 2006)

Biochar blended with manure/straw compost has also been shown to substantially reduce N losses during the composting process due to its effect on nutrient sorption. Like straw, biochar can increase the adsorption of N and prevent NH_3 volatilization and this effect from biochar can be many times greater than that of straw due its high adsorption capacity or CEC. Studies on compost showed total N losses could be reduced by 52% with the addition of biochar (Steiner et al. 2010).

When biochar is returned to the field, its effects on total GHGEs; however, are mixed—possibly due to the variable quality of biochar products and dynamic conditions of soil. A meta-analysis of 61 studies on biochar of various feedstocks showed that GHGEs in paddy rice were: −5% for CO_2, −20% for N_2O, but +19% for CH_4 (P < 0.05) with the addition of biochar (Song et al. 2016). Conversely, another meta-analysis of 42 studies showed that biochar reduced CH_4 in acidic soils (Jeffrey et al. 2016). A CH_4 reduction along with a 50–70% reduction in the total C footprint for rice production was also reported in a life cycle assessment study comparing open-field straw burning to straw biochar (Mohammadi et al. 2016). A meta-analysis of 29 studies comparing biochar effects among cropping systems showed that biochar reduced GHGI (yield-scaled emissions) by 41% in upland soils and 17% in paddy soils (Liu et al. 2019).

In light of those studies with large emissions reductions, some authors suggest biochar could potentially mitigate emissions of CO_2, CH_4, and N_2O by a maximum of 1.8 Pg CO_2 eq year^{-1} (12% of current anthropogenic CO_2 eq emissions; 1 Pg = 1 Gt), and total net emissions over the course of a century by 130 Pg CO_2 eq (Das et al. 2014). Theoretically, this makes biochar one of the top mitigation options for rice straw management. Still, more evidence is needed on the feasibility of biochar in CSA, especially as many studies suggest it is cost-prohibitive due to the large volume (around 6 t ha^{-1}) of biochar needed in-field to achieve mitigation.

9.4 Other Off-Field Practices and Effects on GHGEs

9.4.1 Mechanized Straw Collection

The use of combine harvesters for rice has expanded rapidly worldwide, and major producers such as Vietnam and Cambodia almost exclusively rely on them (Gummert et al. 2018). This has large implications for rice straw management and its associated indirect and direct effects on GHG emissions. Contrary to traditional harvesting systems that use threshers and pile straw for easy collection, combine harvesters spread rice straw on the field. This hampers manual collection, thus promoting straw incorporation and increased CH_4 emissions. Additionally, the added emissions from fuel consumption and machine production range around 60–165 kg CO_2 eq t^{-1} of collected straw (Nguyen et al. 2016).

9.4.2 Fodder

Enteric fermentation as CH_4 from livestock is the leading source of agricultural emissions and accounts for about 5.8% of total anthropogenic emissions (Gerber et al. 2013). The quality of ruminant feed has a significant effect on this emission intensity. Rice straw fodder, although used widely across Asia, is particularly inefficient as a ruminant feed. Its low digestibility equates to high yield-scaled CH_4 emissions compared to more high-quality fodder, such as cowpea straw (Hristov et al. 2013). In fact, rice straw as fodder has been shown to increase GWP 13% compared to straw burning (Launio et al. 2016). Because of the widespread use of rice straw as fodder, it can be assumed that its contribution to emissions from enteric fermentation is significant. Improving the digestibility of poor-quality fodder, such as rice straw, may be one of the most effective emissions mitigation strategies for

livestock according to Gerber et al. (2013). Research suggests that the digestibility of rice straw could be improved by up to 20% by pretreatment methods, such as nutrients and inoculants (Sarnklong et al. 2010). In cattle, a 1% increase in straw digestibility equates to a 4% increase in growth rate and proportional drop in yield-scaled emissions.

9.4.3 Bioenergy

9.4.3.1 Straw Combustion for Thermal Bioenergy

Rice straw can serve as a low-cost and renewable fuel source for combustion power plants. According to LCA on the use of rice straw as thermal bioenergy in Thailand, emissions can be reduced by 1.79 kg CO_2 eq kWh^{-1} compared to coal power and 1.05 kg CO_2 eq kWh^{-1} compared to natural gas-based power generation. Delivand et al. (2011) found that substituting natural gas or coal fuels with rice straw fuels for power generation would result in a considerable fossil fuel savings and lower GHGEs. It was estimated that 0.378 tCO_2 eq t^{-1} straw and 0.683 tCO_2 eq t^{-1} straw could be avoided if rice straw substitutes natural gas or coal in the power generation sector, respectively.

9.4.3.2 Straw Anaerobic Digestion for CH_4 Bioenergy

Agricultural residues, such as rice straw, offer a valuable alternative feedstock for biogas production since they contain a considerable amount of carbon that is beneficial for anaerobic codigestion with animal manure (Mussoline et al. 2012). Anaerobic digestion (see more details in Chap. 5) is a biological process that can degrade waste organic material by the concerted action of a wide range of microorganisms in the absence of oxygen. The process converts a large portion of rice straw into biogas, which is typically a mixture of methane (60%) and carbon dioxide (40%). If captured, biogas can be utilized as a clean fuel for heat and power generation. In principle, anaerobic digestion is an attractive option for mitigating the CH_4 associated with straw incorporation. However, in actual practice, particularly for small-scale anaerobic digestion, the technology has not proven efficient enough to be the most feasible mitigation strategy. Improving the technology to reduce leakage and match the digester capacity to biogas use in small-scale applications may be required to be a viable mitigation option.

Regarding the use of rice straw for bio-ethanol production, a review by Cheng and Timilsina (2011) reported that all advanced biofuel technologies have the advantage of producing fuels with almost zero or very little net emissions to the atmosphere.

9.5 Conclusions and Recommendations

Lowland rice contributes 10% of the global agricultural GHGEs due to CH_4 production from anaerobic decomposition of organic material. Straw management is therefore a key factor for controlling global agricultural emissions. Incorporating rice straw under flooded conditions leads to high CH_4 emissions. Burning, although a standard practice with lower GHGEs than incorporating, is not considered a CSA option due to its negative effect on soil nutrients, SOC, and air pollution. Water management through AWD is a major GHG mitigation strategy that can reduce 48% of the CH_4 and thus is an effective method to reduce emissions when straw is incorporated under flooded conditions. AWD in combination with early incorporation can further reduce CH_4 emissions by 80%. The rate of straw incorporation to achieve CSA, however, is highly dependent on environment. Rice–upland crop rotations or rice systems with prolonged fallow periods benefit from greater rates of straw incorporation due to losses in SOC. High rates of straw incorporation under aerobic conditions can sequester SOC with a minimal increase in emissions compared to incorporation under flooded conditions. Practices that optimize SOC sequestration while minimizing emissions, such as early straw incorporation with AWD water management could be an important step towards carbon neutral rice systems.

Off-field practices such as composting, biochar, and bioenergy offer potentially larger mitigation opportunities than in-field practices. Composting, for example, can mitigate both emissions associated with fresh straw incorporation and those associated with livestock manure and fertilizer use. The combination of biochar and compost can further enhance mitigation. Although effective, off-field technologies may be limited due to the added costs of straw transport, capital equipment and labor.

Depending on site-specific conditions related to economics, climate, soil type, and infrastructure, a combination of off-field and in-field straw management practices is needed to reduce emissions from rice production. More holistic and cross-sectoral studies, e.g., through life-cycle assessment, are needed to determine the full GHG budget of certain site-specific straw management options. Additionally, MACC and CBA studies would be important to develop clear technical and policy recommendations that also consider the economics of CSA and straw management.

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