Meta-analysis of the effect of water and straw management practices on methane emissions from rice fields

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Running title

Rice management practices and methane emissions

Abstract

Rice fields contribute substantially to global warming of the atmosphere through the emission of methane (CH_4). This paper reviews the state-of-the-art of factors affecting CH_4 emissions in rice fields, focusing on soil organic matter content and water management practices. It establishes a quantitative relationship between these factors based on a literature survey through a meta-analysis, useful to update the emission factors used to estimate CH_4 in National Emission Inventories. Methane emissions in rice fields can be as much as 90% higher in continuously flooded rice fields compared with other water management systems, independent from straw addition. Water management systems which involve absence of flooding in total or part of the growing period such as midseason drainages, intermittent flooding and percolation control can reduce CH_4 emissions substantially. Moreover, CH_4 emissions increase with the amount of straw added until 7.7 t/ha for continuously flooded soils and until 5.1 t/ha for other water regimes. Above these levels, no further increase is produced with further addition of straw. As regards to rice straw management mitigation strategies, recommended practices are: composting rice straw, straw burning under controlled conditions, recollecting rice straw for biochar production, generation of energy, to be used as a substrate, or to obtain other by-products with added value. This review improves the understanding of the relationship between straw application rate, water regimes and CH_4 emissions from rice fields to date. This relationship can help to select the most appropriate management practices to improve current mitigation strategies to reduce atmospheric CH_4.

Keywords: atmospheric pollution, greenhouse gases, paddy field, regression modeling, water regime.

1. Introduction

The mitigation of greenhouse gas emissions from agriculture is a major focus nowadays. In accordance with the Kyoto protocol (1997), nations are not only obliged to reduce greenhouse gas emissions, but also to report on them in The National Greenhouse Gas Emission Inventories. Among agricultural sources, rice fields release annually about 60 to 100 million tons of methane (CH_4) worldwide, which represent from 5 to 20% of the total anthropogenic CH_4 emission (Aulakh *et al*., 2000; IPCC, 2006). Considering that CH_4's global warming potential is 23 times higher than carbon dioxide (CO_2) (IPCC, 2006), rice fields can contribute substantially to global warming of the atmosphere. Moreover, rice paddies can be expected to continue to be major sources of CH_4 in the future, due to the need to feed the increasing human population and thus to increase rice yield and its harvested area (Minamikawa *et al*., 2006). This is especially relevant in Southern Asian countries, where rice cultivation represents a relatively large surface area, and in specific localized production regions like in Spain, Italy or North America. Therefore, there is a strong need for economically viable and environmentally sustainable ways of cultivating rice, which imply improving straw and water management practices and reducing CH_4 emissions.

The amount of straw applied and the continuously flooded water management exert a strong influence on CH_4 emissions (Yan *et al.*, 2009). However, knowledge on the effect of the type of organic matter, especially on the dose and quality of rice straw, on CH_4 emission from rice fields is still limited. Moreover, information on the combined effect of the addition of rice straw (increasing soil organic matter content) with varying water regimes is missing.

The aim of this paper is therefore, to review the state-of-the-art of factors affecting CH_4 emissions in rice fields, focusing on two management factors: soil organic matter content (affected by the addition of straw and its management) and water management practices. Furthermore, it establishes a quantitative relationship between these management factors influencing CH_4 emissions based on a literature survey through a meta-analysis. This quantitative relationship can help to select the most appropriate management practices to improve current mitigation strategies to reduce atmospheric CH_4 from rice cultivation and hence contribute to reduce its environmental impacts.

2. Factors affecting methane emission in rice fields

The emission of CH_4 from rice fields results from a complex process where the organic matter in the soil is anaerobically broken down, and CH_4 is finally produced as a by-product in the metabolism of methanogenic archaea. Anaerobic conditions arise from the flooding of fields, which considerably decreases the availability of oxygen in the soil (Conrad, 1993; Neue, 1997; Watanabe *et al*., 2001). Once CH_4 is formed in rice soils, it can be released to the atmosphere through three pathways: ebullition, molecular diffusion and transport through the rice plant (Neue *et al*., 1994; Khalil and Shearer, 2006) (Fig. 1).

Methane fluxes in rice fields show distinct diurnal and seasonal variations. Moreover, the emission of CH_4 from rice fields depends on different factors, summarized in Fig. 1, such as water regime (Kang *et al.,* 2002; Cai *et al.,* 2003; Zhang *et al.,* 2011), frequency, dosage and type of fertilization (Krüger and Frenzel, 2003; Nayak *et al*., 2006; Ma *et al.,* 2007), soil organic matter content (Naser *et al*., 2007; Ma *et al*., 2009; Wang *et al.,* 2010), rice cultivar and plant activity (Setyanto *et al*., 2004; Jia *et al*., 2006; Khosa *et al.,* 2010), temperature (Wang and Li, 2002; Watanabe *et al*., 2005) and soil properties such as texture, pH, redox potential, and carbon/nitrogen ratio among others (Neue and Roger, 2000; Setyanto *et al*., 2002; Xu *et al*., 2003).

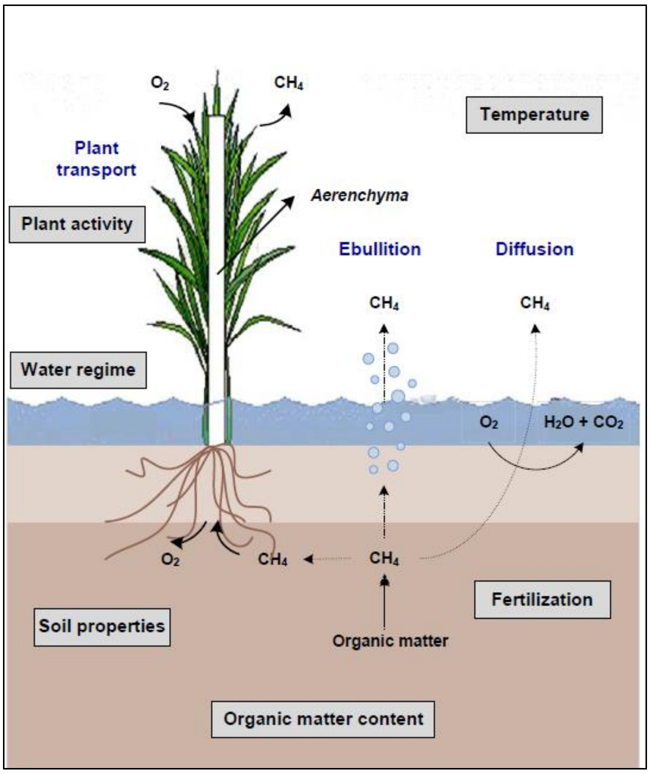

Fig. 1 Factors affecting methane emissions from rice fields

Among the factors shown in Fig. 1, organic matter content and water regime are recognized as the most influencing field management practices affecting CH_4 emissions from rice fields (Majumdar, 2003; Yan *et al*., 2005; Minamikawa *et al*., 2006; Zhang *et al*., 2011).

Water management in rice cultivation is highly site-specific and depends on water availability and traditional cultural practices. In fact, water regime (irrigation and drainage) affects directly soil characteristics, preventing or promoting the development of reductive conditions. The presence of standing surface water is essential for the development of the anaerobic conditions in paddy soil by limiting the transport of atmospheric oxygen into soil, which is favorable for CH_4 production (Yagi *et al*., 1996; Bharati *et al*., 2001; Singh *et al*., 2009). Consequently, CH_4 mitigation strategies from rice fields must consider rice agricultural practices and water regimes which reduce or limit the flooded period.

As regards soil organic matter content, readily mineralizable organic matter in the soil also constitutes a major source for CH_4 formation in paddies (Neue *et al*., 1995). The available carbon in the soil from residues of previous crops is one of the main CH_4 production sources. Therefore, the addition of organic matter such as rice straw into a flooded rice field provides an extra source of carbon, which can serve as substrate for methanogenic activity (Wassmann *et al*., 1993b). Furthermore, soil organic matter enhances the reduction of soils, contributing to the production of CH_4 (Denier Van der Gon and Neue, 1995). The effect of organic matter addition is more pronounced in soils with low intrinsic organic matter content.

Although the relationship between CH_4 emissions and straw application has been reported in several studies carried out in Italy (Schütz *et al*., 1989), Japan (Yagi and Minami, 1990; Naser *et al*., 2007; Xu and Hosen2010), United States (Cicerone *et al*., 1992; Bossio *et al*., 1999; Kongchum *et al*., 2006), China (Hou *et al*., 2000; Lu *et al*., 2000; Zou *et al*., 2005; Wang *et al*., 2010; Zhang *et al*., 2011), Thailand (Chareonsilp *et al*., 2000; Vibol and Towprayoon, 2010), India (Jain *et al*., 2000; Khosa *et al*., 2010), and Philippines (Neue *et al*., 1994; Denier Van der Gon and Neue, 1995); knowledge gaps related with the combined effect of the type, dose, and quality of rice straw with varying water regimes still remain.

3. Relationship between water and straw management practices on methane emissions: a meta-analysis

Over the past 20 years, research studies have been conducted to give insight into the effect of water and straw management practices on CH_4 emissions from rice fields. Table 1 compiles reported CH_4 emission rates (ER) related to these rice management practices based on a literature survey. The survey was performed from a total of 149 ER values from 24 published research papers in eight countries, Four water management practices were identified: continuously flooded, non-flooding irrigated, rainfed, and intermittently flooded. Reported straw incorporation rates in the literature show a wide range, from 0 to 12.5 t/ha. Table 1 shows the ER values as well as the seasonal emission factor (EF) for each source and location, accounting for specific water regime and straw rate incorporation. Methane ER ranged from 0.1 to 952 mg/m^2/day.

Table 1 Methane emission rates (ER) and seasonal emission factors (EF) reported in the literature with varying water management practices and addition of straw rates in descending chronological order

Location	**Water regime**[a]	**Straw rate**	**ER**	**Seasonal EF**	**Source**
		(t/ha)	**(mg CH_4/m^2/day)**	**(kg CH_4/ha/year)**	
India	Cont. and int. flood	0	11 - 53	11.9 - 58.83	Khosa *et al*. (2011)
China	Cont. and int. flood	0 - 4.8	197 - 544	302 - 832	Zhang *et al*. (2011)
India	Irrigated	0 - 10	20 - 213	21.8 - 229.8	Khosa *et al*. (2010)
China	Cont. flood	0 - 10.6	241- 538	255 - 570	Wang *et al*. (2010)
China	Int. flood	0 - 3.75	39 - 657	50 - 828	Ma *et al*. (2009)
China	Int. flood	0 - 4.8	55 - 216	69.3 – 272.2	Ma *et al*. (2008)
China	Int. flood	0 - 3.75	30 - 544	40.5 - 712.6	Ma *et al*. (2007)
Japan	Cont. flood	0 - 2.19	31 - 456	40.4 - 408	Naser *et al*. (2007)
Japan	Cont. and int. flood	4	93 -273	116 - 341.3	Saito *et al*. (2006)
China	Cont. and int. flood	0 - 2.25	72 - 186	85 - 220	Zou *et al*. (2005)
Japan	Cont. and int. flood	0 - 3	43 - 502.7	46.7 - 502.7	Goto *et al*. (2004)
Philippines	Irrigated and rainfed	0 - 5	35 - 565.7	35 - 565.7	Wassmann *et al*. (2002)
Thailand	Irrigated and cont. flood	0 - 12.5	22 - 311	22 - 619	Chareonsilp *et al*. (2000)
Philippines	Cont. flood	0 - 4	165 - 952	160 - 952	Corton *et al*. (2000)
China	Int. flood	0 - 1.7	167 - 280	141.9 – 279.4	Lu *et al*. (2000)
Indonesia	Rainfed	0 - 6.1	52 - 80	53 - 78	Setyanto *et al*. (2000)

Location	Water regime[a]	Straw rate	ER	Seasonal EF	Source
		(t/ha)	(mg CH_4/m^2/day)	(kg CH_4/ha/year)	
China	Int. flood	0 - 1.3	4 - 100	6 - 141	Wang *et al*. (2000)
USA	Int. flood	9.8	96 - 103	118.3 - 126.9	Bossio *et al*. (1999)
Japan	Cont. and int. flood	5.8	8 - 216	30 - 790	Kanno *et al*. (1997)
Japan	Cont. flood	0 - 6	54 - 807	54 - 807	Chidthaisong *et al*. (1996)
India	Irrigated	1	0.1	0.1	Singh *et al*. (1996)
Thailand	Rainfed and int. flood	0 - 0.31	6 - 238	6 - 214	Jermsawatdipong *et al*. (1994)
Japan	Int. flood	0 - 9	10 - 326	11 - 448	Yagi y Minami (1990)
Italy	Int. flood	3 - 12	230 - 680	242 - 767	Schütz *et al*. (1989)

[a] Int. flood: intermittently flooded; Cont. flood: continuously flooded.

To analyze the effect of straw addition and water management on CH_4 emissions, the values presented in Table 1 were related using a weighted quadratic regression model. In the model, reported seasonal EF were used as dependent variable and each water management practice and straw dose were used as independent variable using Proc Reg of SAS software (SAS, 2009). Average values for each straw incorporation rate were used. The selection of this model was based on the literature, where CH_4 emissions have been reported to increase with straw addition until certain value where no further increase in emissions occurs with further addition of straw (Schütz *et al*., 1989; Kludze and DeLaune, 1995). As a result, the regression equation indicated in Eq 1 was obtained:

$$EF = \beta_0 + \beta_1 \cdot Straw + \beta_2 \cdot Straw^2 + \beta_3 \cdot Cont.flood + \beta_4 \cdot Straw \ x \ Cont.flood + \varepsilon \qquad \text{(Eq 1)}$$

where EF is the methane emission factor (kg CH_4/ha/year), β_0 is the intercept of the regression model; β_1 is the regression coefficient of the linear effect of straw incorporation (straw, t/ha); β_2 is the regression coefficient of the quadratic effect of straw incorporation (straw, t/ha); β_3 is the coefficient for a dummy variable defining the effect of continuous flooding on CH_4 emission, and β_4 is the linear effect of straw incorporation in continuous flooding, with respect to the other alternatives. Finally, ε is the model error.

Table 2 shows the results of the regression modeling. Results from the quadratic regression model showed a significant effect ($p<0.001$) of straw addition rate on CH_4 emissions. The effect of continuous flooding was significantly different from the other water management practices ($p<0.05$). However, intermittently flooded, non-flooding irrigated, and rainfed water management did not differ significantly among them ($p>0.05$) in terms of CH_4 emissions.

Table 2 Effect of straw addition rate and water management practices on methane emissions. The model was significant at $p<0.0001$ ($R^2 = 0.85$).

Parameter	Estimate	Standard error	t Value	P > t
Independent term (β_0)	82.9	17.5	4.73	< 0.001
Straw rate (β_1)	69.1	10.2	6.78	< 0.001
Straw rate^2 (β_2)	-6.70	1.25	-5.37	< 0.001
Continuously flooded (β_3)	77.1	32.8	2.35	0.028
Straw rate x Cont.flood.(β_4)	34.2	8.8	3.89	< 0.001

According to Table 2, the following regression equations can be used to predict CH_4 emission factor within the range of straw incorporation rate from 0 to 10 t/ha. In continuously flooded rice fields, the model corresponds to Eq. 2, when the variable Cont.flood. equals 1. Eq 3 explains CH_4 emissions from paddies when water management is rainfed, intermittently flooded or non-flooding irrigated (when the variable Cont.flood. equals 0):

$$EF_{\text{continuously flooded}} = 160.0 + 103.3 \text{ straw rate} - 6.70 \text{ straw rate}^2 \qquad \text{(Eq 2)}$$

$$EF_{\text{other water regimes}} = 82.9 + 69.1 \text{ straw rate} - 6.70 \text{ straw rate}^2 \qquad \text{(Eq 3)}$$

Fig. 2 shows the graphical representation of the quadratic regression model obtained from the literature survey. According to the model, average CH_4 emissions in rice fields where no straw had been incorporated (e.g. straw was burned or removed) were 82.9 kg CH_4/ha/year, using either rainfed, intermittently flooded, or non-flooded irrigated water management. However, CH_4 emissions were on average 93% higher (160 kg CH_4/ha/year) in continuously flooded rice fields where no straw had been incorporated, which is significantly higher than in other water management systems. This indicates that continuous flooding can promote conditions for CH_4 formation, independent from the addition of organic matter into the soil. Consequently, CH_4 emissions can arise from other organic matter sources such as roots and organic compounds supplied by root exudation and biomass litter, including leakages, secretions, mucilage, mucigel and lysates (Schütz *et al*., 1991; Aulakh *et al*., 2001). Compounds leaked from roots normally include carbohydrates, organic acids and amino acids (Vancura and Hovadik, 1965). As a result, those water management systems which involve water regimes different from continuously flooded management (absence of flooding in total or part of the growing period) present lower CH_4 emissions compared with continuously flooded management system independent from the amount of organic matter incorporated. The meta-analysis confirms that water management practices have a strong influence on the process involved in CH_4 emission from rice fields.

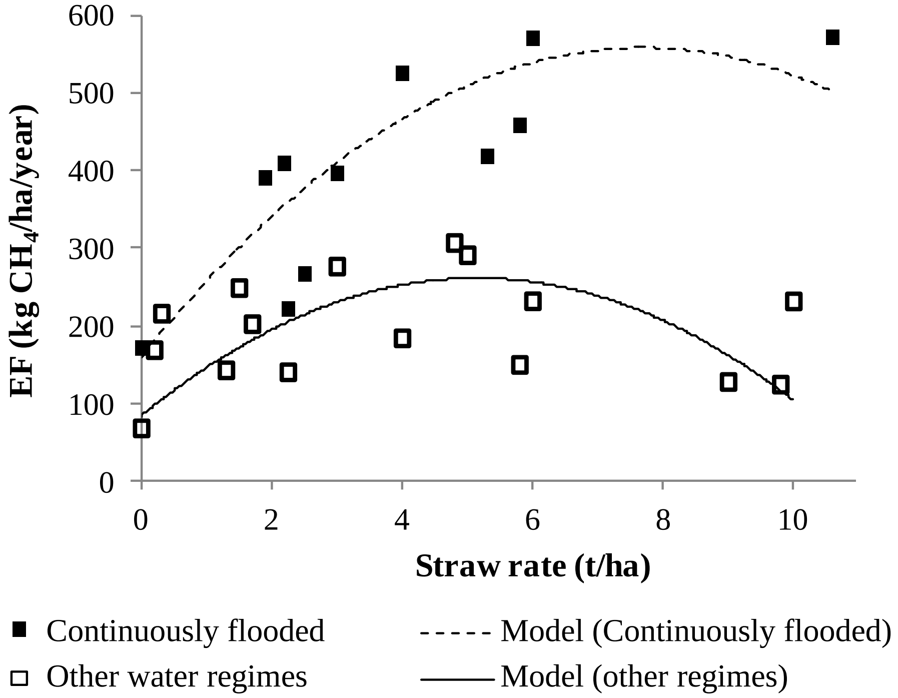

Fig. 2 Regression model of methane emissions in rice cultivation based on straw addition rate and water management practices.

Regarding straw addition rate, results from the meta-analysis showed that the addition of straw increased CH_4 emissions differently depending on the water management regime. In those systems without permanent flooding, CH_4 emissions increase with rice straw incorporation up to a maximum of approximately 5.1 t/ha of incorporated straw, corresponding to about 261 kg CH_4/ha/year. This straw application rate is common in rice fields; however, this value could vary for each country on the basis of the rice or wheat straw yield. Above 5 t/ha, no further increase in CH_4 emissions is produced with further addition of straw. For continuous flooding, the maximum emission is produced at a higher straw application rate, equal to 7.7 t/ha (corresponding to about 481 kg CH_4/ha/year).

This behavior corresponds to a law of diminishing returns, which is common in many agricultural scenarios. When straw is incorporated at low rates, the increase of organic matter in the soil considerably enhances methanogenic activity with respect to no application of straw. However, as long as organic matter increases, it is not longer the limiting factor for CH_4 emissions, and the emission process is then limited by other factors related with the activity of methanogenic archaea. Wassmann *et al*. (1998) explained that the dynamic changes in soils with high CH_4 production rates can be attributed to intense bacterial degradation of organic material exceeding the availability of oxidants. Therefore, the inherent CH_4 production capacity may be determined by an interaction of various chemical and physical parameters under anaerobic conditions.

Even more, CH_4 generation from rice fields can decrease at very high straw incorporation rates if the excess of organic matter obstructs the usual pathways of CH_4 formation. This decrease in CH_4 may be the consequence of the formation of phytotoxic substrates in the soil, which are formed at high organic carbon contents (Takai and Asami, 1962; Hollis and Rodriguez-Kabana, 1967) and may inhibit plant development and, consequently, CH_4 emission.

The emission model obtained in this study seems to be consistent with reported emission values within the range of straw application rate from 0 to 10 t/ha, but contradictory results were found for higher straw incorporation rates. Several authors have observed a similar trend as shown in the dose-response curve presented in Fig. 2. Schütz *et al*. (1989) reported that application of rice straw at 5 t/ha and 12 t/ha increased CH_4 rates by factors of 2.0 and 2.4, respectively, compared with no addition of straw. However, adding as much as 24 t/ha of rice straw did not increase CH_4 emissions with respect to 12 t/ha. In the same way, Kludze and DeLaune (1995) reported that application of rice straw at 11 t/ha enhanced CH_4 emissions compared with no addition of straw, whereas 22 t/ha retarded CH_4 emissions. However, Chareonsilp *et al.* (2000) found very low and variable CH_4 emissions for a straw incorporation rate of 12.5 t/ha under continuous flooding. According to these observations, further studies are required to quantify more precisely how high incorporation rates (>10 t/ha) interact with different water regimes.

Other researchers have observed a linear relationship between CH_4 emission and the amount of straw incorporated (Cicerone *et al*., 1992; Wang *et al*., 1992; Xu *et al*., 2003; Watanabe *et al*., 2005; Naser *et al*., 2007; Gogoi *et al*., 2008), however, results from the meta-analysis show that increasing organic matter inputs will only stimulate CH_4 emission until a certain value, when other factor than organic carbon availability seems to become limiting (Denier Van der Gon and Neue, 1995). Nevertheless, although straw addition and water management are significant factors influencing CH_4 emission from rice fields, other factors such as mineral fertilizer, the variety of rice, the type of soil and environmental conditions may also considerably affect CH_4 emission.

4. Mitigation strategies based on water and straw management practices

Mitigation of greenhouse gases is mandatory and so is its estimation. To reduce CH_4 from rice fields, all influencing factors with its synergies and antagonisms must be studied. So far, CH_4 estimations in National Greenhouse Gas Emission Inventories are based on the methodology proposed by the Intergovernmental Panel on Climate Change (IPCC) Guidelines (IPCC, 2006). The results from this review and the regression equations which derive from the meta-analysis can be useful to update the CH_4 emission factor proposed in IPCC (2006). Current IPCC emission factor is based on studies carried out by Yan *et al*. (2005), which revised emission and scaling factors from an updated analysis of a large data set of field studies until 2003. Our results improve the relationship between the straw application rate, water regimes, and CH_4 emissions from rice fields to date. Our model describes more precisely how straw incorporation, water regime and their interaction are affecting CH_4 emissions, according to literature data.

In this framework, possible strategies to reduce CH_4 emission from rice cultivation can be implemented by controlling production, oxidation or transport processes through the plant, as shown in Fig. 1. These options include: managing water regime and straw addition, establishing an adequate fertilization program, using nitrification inhibitors, changing tillage practices, including crop rotation and selecting less vigorous rice varieties (Aulakh *et al*., 2000; Wassmann *et al.*, 2000; Majumdar, 2003; Minamikawa *et al*., 2006; Yan *et al.*, 2009). However, mitigation strategies should be effective, technically and economically applicable and easily understood and accepted by farmers. If possible, these techniques should also increase rice yield (Majumdar, 2003). As a result from this review, straw and water management practices have been identified as key factors affecting CH_4 emissions, and consequently mitigation strategies should focused on these factors.

4.1. Water management strategies

Continuous flooding increases CH_4 emissions regardless straw addition. Several studies have focused on management strategies to mitigate these emissions without compromising rice yields, such as limiting irrigation and allowing the standing water to drain from the field. However, mitigation options through water management can vary depending on different factors, such as: soil texture, percolation rate, frequency of drainage, duration of dry period and soil redox potential (Cai *et al*., 1997; Majumdar, 2003; Minamikawa *et al*., 2006).

Previous research has demonstrated that midseason aeration of rice paddy fields can reduce CH_4 emission by about 50% (Kimura *et al*., 1992; Kanno *et al*., 1997; Yagi *et al*., 1997; Wassmann *et al.*, 2000; Cai *et al.*, 2003). Sass *et al*. (1992) and Kimura *et al*. (1991) observed that a single midseason drainage may reduce seasonal emission rates by about 50%. Bronson *et al*. (1997) reported that midseason drainage at maximum tillering or panicle initiation suppressed CH_4 emissions. However, midseason drainage is not feasible during periods of heavy rainfall and when excess water is not available to flood the field again. Therefore, in case of non-availability of water for re-flooding, it has limited applicability in time and space (Singh *et al*., 2009).

Draining paddy fields which used to be under continuous flooding in the fallow season significantly decreases CH_4 emission from the fields (Cai *et al.*, 2003; Xu *et al*., 2000). This technique is able not only to stop directly CH_4 emission from the rice fields in the fallow season, but also to reduce CH_4 emission substantially during the following rice season (Cai *et al.*, 2003). However, the rice yields in fields drained in the fallow season may be compromised compared with permanently flooded fields (Zhang *et al.*, 2011).

Techniques including intermittent irrigation can also reduce CH_4 emissions improving soil permeability and increasing soil redox potentials, which often result in increased rice yield (Wang *et al*., 1999). Jain *et al*. (2000), Buendia (1997) and Sass (1992) observed that CH_4 emissions decreased in 28%, 55% and 88% respectively, when intermittent irrigation was applied. Moreover, in most cases this practice did not reduce rice yield but required more water than the normal floodwater treatment.

However, soil aeration requires more water than continuous flooding regime (Sass *et al*., 1992). Furthermore, drainage techniques must be managed carefully to prevent losses of nitrogen corresponding with nitrous oxide (N_2O) emissions, a very active greenhouse gas (Wassmann *et al*., 1993a; Abao *et al*., 2000; Zou *et al.*, 2005). These emissions could be increased through nitrification and denitrification processes, which are associated with soil drying and wetting, respectively (Neue, 1993; Bronson *et al.*, 1997; Corton *et al*., 2000).

Methane emission rates decrease as the percolation rates increase by improving soil physical properties or by using under-ground pipe drainage (Yagi *et al*., 1997;

Minamikawa and Sakai2006). Therefore, reducing water depth and time of flooding by maintaining the soil saturated without standing water could be a technically feasible and agronomically and environmentally appropriate alternative to reduce CH_4 emissions (Rath *et al.,* 1999; Lemer and Roger, 2001).

4.2. Straw management strategies

A promising strategy to mitigate CH_4 emissions consists in the integration of intermittent irrigation techniques and of organic matter management (Wang *et al*., 1999; Zou *et al.,* 2005). Alternative uses of straw crop residue should be considered as regards straw management.

Straw incorporation practices alter organic matter availability. The kind, rate timing and degree of maturation of organic matter affect the magnitude of CH_4 emission (Minamikawa *et al*., 2006). Moreover, the addition of straw has been associated with putrefaction processes releasing sulfur gases that can generate odor nuisances, harmful effects on aquatic organisms, and transmission of crop diseases *(*Chareonsilp *et al*., 2000; Tanji *et al*., 2003; Yi *et al*., 2008). In addition, straw incorporation could promote reducing conditions under which toxic products such as sulfides may be produced, causing toxicity to rice plants (Gao *et al*., 2004). Reducing the amount of labile organic matter in soils by composting organic substrates or promoting aerobic decomposition of biomass is considered as one of the effective means of mitigating CH_4 emission in soils (Corton *et al*., 2000; Majumdar, 2003). However, this could increase nitrous oxide emission by nitrification of released ammonium (Flessa and Beese, 1995).

An alternative method of disposing rice straw is to apply it off-season. According to the 2006 IPCC guidelines, rice straw applied off-season produces less CH_4 emission than if rice straw is applied just before rice transplanting (Yan *et al.,* 2009). Consequently, incorporation of rice straw in the fallow season instead of the rice season is recommended as an option to reduce CH_4 emission from rice fields (Lu *et al*., 2000; Xu *et al*., 2000).

The type of organic matter applied to the soil affects CH_4 emission. Wassmann *et al.*, (1993a) observed that applying residues from a biogas generator CH_4 emissions decreased by approximately 60% as compared to fresh organic amendments and 52%, compared to the combination of urea and organic amendments. According to Chareonsilp *et al*. (2000), burning straw instead of incorporating it directly reduces CH_4 emission by 89%. According to these authors, zero tillage and mulching also reduced emissions when compared with fresh straw incorporation. Moreover, straw burning poses several benefits for the farmer since it controls weed and crop diseases, prepares fields for the next harvest and releases nutrients for the next crop (Lemieux *et al*., 2004; Cheng *et al*., 2009; Gadde *et al*., 2009).

Straw burning, however, produces high amounts of CO_2, as well as considerable amounts of carbon monoxide (CO), CH_4, nitrogen oxides (NO_x), sulfur oxides (SO_x), non-methane hydrocarbons (NMHC), dioxins, polycyclic aromatic hydrocarbons (PAHs) and particulate matter (Gadde *et al*., 2009). The emission of these pollutants during open burning of crop residues can cause relevant local air pollution problems and severe impacts on human health (Gullett and Touati, 2003; Hays *et al*., 2005; Lin *et al*., 2007), for example bronchial asthma (Arai *et al*., 1998; Torigoe *et al*., 2000). Some of these air pollutants have significant toxicological properties and are considered potential carcinogens (Gadde *et al*., 2009). Due to the growing concern for air quality related with rice straw burning, this practice has been restricted in some parts of the world. Therefore, in most cases, straw burning can not be recommended as a CH_4 mitigation option.

It has been demonstrated that rice straw is not suitable for animal nutrition unless treated to improve its feeding value (Doyle *et al.*, 1986; Bae *et al.*, 1997). However, the high interest for re-using the large amount of rice straw generated worldwide has resulted in a wide variety of other potential treatments. Perhaps the most traditional use is the generation of energy (Zhang and Zhang, 1999; Okasha, 2007). A variety of technologies have been developed which include from direct burning to pyrolysis techniques to transform rice straw in a more versatile energy source (Pütün *et al*., 2004), producing different by-products such as biochar which could help to improve soils, avoid CH_4 emissions, and sequester carbon in rice soils (Zhang *et al*., 2010; Haefele *et al*., 2011; Liu *et al*., 2011) .

Rice straw has also been used for mulch production and as a substrate for mushroom production (Zhang *et al*., 2002). More recently, a variety of technologies have been developed to obtain other by-products with added value. Rice straw has been used to obtain xylitol (Mayerhoff *et al*., 1997), sugars (Karimi *et al*., 2006), cellulose and lignine pulp (Rodríguez *et al*., 2008) and enzymes such as laccase (Niladevi *et al*., 2007). The potential of rice straw to produce natural fibers has been also investigated (Reddy and Yang, 2006), and it has been successfully used to produce biopolymers in combination with PVC (Kamel, 2004) and polypropylene (Grozdanov *et al*., 2006), or as a construction material with isolation properties (Yang *et al*., 2003).

However, the harvesting of straw from rice fields continues to be a major challenge. Therefore, although several alternative management strategies are available for it, the harvesting of rice straw implies using different agricultural machinery and an additional economical cost to be paid by farmers.

To optimize straw management, it is essential to improve our knowledge on crop characteristics, to develop a group of mitigation strategies to minimize emissions to the atmosphere as well as to maximize rice production and yield, without considerably modifying culture practices.

5. Conclusions -Recommendations

As a result from the review of the state-of-the-art of factors affecting CH_4 emissions in rice fields and a meta-analysis on how soil organic matter content (affected by the addition of straw and its management) and water management practices influence CH_4 emissions; the following conclusions can be extracted:

Continuous flooding can promote conditions for CH_4 formation, independent from the addition of organic matter into the soil. Methane emissions in rice fields where no straw has been incorporated are 90% higher in continuously flooded rice fields compared with other water management systems such as rainfed, intermittently flooded, or non-flooding irrigated.

Water management systems other than continuously flooded are recommended to reduce CH_4 emissions. The recommended water management mitigation strategies are: midseason drainages, intermittent flooding, and percolation control.

Methane emissions increase with straw incorporation rates up to 5.1 t/ha of incorporated straw, under non-permanent flooding conditions. For continuously flooded soils, CH_4 increased with straw incorporation up to 7.7 t/ha. Above these levels, no further increase in CH_4 emissions is produced with further addition of straw for straw addition between o t/ha to 10 t/ha. Further studies are required to quantify more precisely how high incorporation rates (>10 t/ha) interact with different water regimes.

As regards to rice straw management mitigation strategies, recommended practices are: composting rice straw, straw burning under controlled conditions, recollecting rice straw for biochar production, generation of energy, to be used as a substrate, or to obtain other by-products with added value.

Our results improve the understanding of the relationship between straw application rate, water regimes and CH_4 emissions from rice fields to date. These data are useful to update the CH_4 emission factor used to estimate CH_4 emissions in the National Greenhouse Gas Emission Inventories.

The main challenge concerning CH_4 mitigation options from rice fields is the difficulty of establishing a single global solution. Mitigation techniques based on straw and water management, however, may achieve relevant reduction and can be effective, technically and economically applicable, easily understood and accepted by farmers. If possible these techniques should also increase rice yield. The effect of mitigation strategies in the light of gaseous pollutants other than CH_4, and the global environmental impact caused by rice cultivation should also be assessed.

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References

Abao, E.B., Bronson, K., Wassmann, R., Singh, U. (2000). Simultaneous records of methane and nitrous oxide emissions in rice-based cropping systems under rainfed conditions. *Nutrient Cycling in Agroecosystems* 58, 131-139.

Arai, T., Takaya, T., Ito, Y., Hayakawa, K., Tshima, S., Shibuya, C., Nomura, M., Yoshimi, N., Shibayama, M., Yasuda, Y. (1998). Bronchial asthma induced by rice. *Internal Medicine* 37, 98-101.

Aulakh, M.S., Bodenbender, J., Wassmann, R., Rennenberg, H. (2000). Methane transport capacity of rice plants. I. Influence of methane concentration and growth stage analyzed with an automated measuring system. *Nutrient Cycling in Agroecosystems* 58, 357-366.

Aulakh, M.S., Wassmann, R., Bueno, C., Rennenberg, H. (2001). Impact of root exudates of different cultivars and plant development stages of rice (Oryza sativa L.) on methane production in a paddy soil. *Plant and Soil* 230, 77-86.

Bae, H. D., McAllister, T. A., Kokko, E. G., Leggett, F. L., Yanke, L. J., Jakober, K. D., Ha, J. K., Shin, H. T., and Cheng, K. J. (1997). Effect of silica on the colonization of rice straw by ruminal bacteria. *Animal Feed Science Technology* 65, 165-181.

Bharati, K., Mohanty, S.R., Rao, V.R., Adhya, T.K. (2001). Influence of flooded and non-flooded conditions on methane efflux from two soils planted to rice. *Chemosphere: Global Change Science* 3, 25-32.

Bossio, D.A., Horwath, W.R., Mutters, R.G., van Kessel, C. (1999). Methane pool and flux dynamics in a rice field following straw incorporation. *Soil Biology & Biochemistry* 31, 1313-1322.

Bronson, K., Neue, H. U., and Singh, U. (1997). Automated chamber measurement of CH_4 and N_2O flux in a flooded rice soil. I. Effect of organic amendments, nitrogen source, and water management. *Soil Science Society of America Journal* 61, 981-987.

Buendia, L.V., Neue, H.U., Wassmann, R., Lantin, R.S. (1997). Understanding the nature of methane emission from rice ecosystems as basis of mitigation strategies. *Applied Energy* 56, 433-444.

Cai, Z., Xing, G., Yan, X., Xu, H., Tsuruta, H., Yagi, K., Minami, K. (1997). Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilisers and water management. *Plant and Soil* 196, 7-14.

Cai, Z. C., Tsuruta, H., Gao, M., Xu, H., and Wei, C. F. (2003). Options for mitigating methane emissions from a permanently flooded rice field. *Global Change Biology* 9, 37-45.

Chareonsilp, N., Buddhaboon, C., Promnart, P., Wassmann, R., Lantin, R.S. (2000). Methane emission from deepwater rice fields in Thailand. *Nutrient Cycling in Agroecosystems* 58, 121-130.

Cheng, M., Horng, C., Su, Y., Lin, L., Lin, Y., Chou, C. (2009). Particulate matter characteristics during agricultural waste burning in Taichung City, Taiwan. *Journal of Hazardous Materials* 165, 187-192.

Chidthaisong, A., Inubushi, K., Muramatsu, Y., Watanabe, I. (1996). Production potential and emission of methane in flooded rice soil microcosms after continuous application of straws. *Microbes and Environments* 11, 73-78.

Cicerone, R.J., Delwiche, C.C., Tyler, S.C., Zimmermann, P.R. (1992). Methane emissions from California rice paddies with varied treatments. *Global Biogeochemical Cycles* 6, 233-248.

Conrad, R. (1993). Mechanisms controlling methane emission from wetland rice fields. Edición: Oremland, R. S. En: *The Biogeochemistry of Global Change: Radiative Trace Gas*. Pag. 317-335. New York, Chapman and Hall.

Corton, T.M., Bajita, J.B., Grospe, F.S., Pamplona, R.R., Asis, C.A., Wassmann, R., Lantin, R.S., Buendia, L.V. (2000). Methane emission from irrigated and intensively managed rice fields in Central Luzon (Philippines). *Nutrient Cycling in Agroecosystems* 58, 37-53.

Denier Van der Gon, H.A.C., Neue, H.U. (1995). Influence of organic matter incorporation in the methane emission from a wetland rice field. *Global Biogeochemical Cycles* 9, 11-22.

Doyle, P.T., Devendra, C., Pearce, G.R. (1986). *Rice straw as a feed for ruminants*.Editors: Doyle, P. T. International Development Program of Australian Universities and Colleges Limited,. Canberra.

Flessa, H., Beese, F. (1995). Effects of sugarbeet residues on soil redox potential and nitrous oxide emission. *Soil Science Society of America Journal* 59, 1044-1051.

Gadde, B., Bonnet, S., Menke, C., Garivait, S. (2009). Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines. *Environmental Pollution* 157, 1554-1558.

Gao, S., Tanji, K.K., Scardaci, S.C. (2004). Impact of Rice Straw Incorporation on Soil Redox Status and Sulfide Toxicity. *Agronomy Journal* 96, 70-76.

Gogoi, N., Baruah, K., Gogoi, B., Gupta, P.K. (2008). Methane emission from two different rice ecosystems (Ahu and Sali) at lower Brahmaputra Valley zone of North East India. *Applied Ecology and Environmental Research* 6, 99-112.

Goto, E., Miyamori, Y., Hasegawa, S., Inatsu, O. (2004). Reduction effects of accelerating rice straw decomposition and water management on methane emission from paddy fields in a cold district. *Soil Science & Plant Nutrition* 75, 191-201.

Grozdanov, A., Buzarovska, A., Bogoeva-Gaceva, G., Avella, M., Errico, M.E., Gentille, G. (2006). Rice straw as an alternative reinforcement in polypropylene composites. *Agronomy for Sustainable Development* 26, 251-255.

Gullett, B.K., Touati, A. (2003). PCDD/F emissions from burning wheat and rice field residue. *Atmospheric environment* 37, 4893-4899.

Haefele, S.M., Konboon, Y., Wongboon, W., Amarante, S., Maarifat, A.A., Pfeiffer, E.M., Knoblauch, C. (2011). Effects and fate of biochar from rice residues in rice-based systems. *Field Crops Research* 121, 430-440.

Hays, M.D., Fine, P.M., Geron, C.D., Kleeman, M.J., Gullett, B.K. (2005). Open burning of agricultural biomass: Physical and chemical properties of particle-phase emissions. *Atmospheric environment* 39, 6747-6764.

Hollis, J.P., Rodriguez-Kabana, R. (1967). Fatty acids in Louisiana rice fields. *Phytopathology* 57, 841-847.

Hou, A.X., Wang, Z.P., Chen, G.X., Patrick, W.H. (2000). Effects of organic and N fertilizers on methane production potential in a Chinese rice soil and its microbiological aspect. *Nutrient Cycling in Agroecosystems* 58, 333-338.

IPCC (2006). *2006 IPCC Guidelines for Greenhouse Gas Inventories*, Prepared by the National Greenhouse Gas Inventories Programme.Editors: Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., y Tanabe, K. IGES, Japan.

Jain, M.C., Kumar, S., Wassmann, R., Mitra, S., Singh, S.D., Singh, J.P., Singh, R., Yadav, A.K., Gupta, S. (2000). Methane emissions from irrigated rice fields in northern India (New Delhi). *Nutrient Cycling in Agroecosystems* 58, 75-83.

Jermsawatdipong, P., Murase, P., Prabuddham, P., Hasathon, Y., Khomthomg, N., Naklang, K., Watanabe, A., Haraguchi, H., Kimura, M. (1994). Methane emission from plots with differences in fertilizer application in Thai paddy fields. *Soil Science & Plant Nutrition* 40, 63-71.

Jia, Z., Cai, Z., and Tsuruta, H. (2006). Effect of rice cultivar on CH4 production potential of rice soil and CH_4 emission in a pot experiment. *Soil Science and Plant Nutrition* 52, 341-348.

Kamel, S. (2004). Preparation and properties of composites made from rice straw and poly(vinyl chloride) (PVC). *Polymers for Advanced Technologies* 15, 612-616.

Kang, G. D., Cai, Z. C., and Feng, X. Z. (2002). Importance of water regime during the non-rice growing period in winter in regional variation of CH_4 emissions from rice fields during following rice growing period in China. *Nutrient Cycling in Agroecosystems* 64, 95-100.

Kanno, T., Miura, Y., Tsuruta, H., Minami, K. (1997). Methane emission from rice paddy fields in all of Japanese prefecture - relationship between emission rates and soil characteristics, water treatment and organic matter application. *Nutrient Cycling in Agroecosystems* 49, 147-151.

Karimi, K., Kheradmandinia, S., Taherzadeh, J. (2006). Conversion of rice straw to sugars by dilute-acid hydrolysis. *Biomass and Bioenergy* 30, 247-253.

Khalil, M.A.K., Shearer, M.J. (2006). Decreasing emissions of methane from rice agriculture. *International Congress Series* 1293, 33-41.

Khosa, M. K., Sidhu, B. S., and Benbi, D. K. (2010). Effect of organic materials and rice cultivars on methane emission from rice field. *Journal of Environmental Biology* 31, 281-285.

Khosa, M. K., Sidhu, B. S., and Benbi, D. K. (2011). Methane emissions from rice fields in relation to management of irrigation water. J*ournal of Environmental Biology* 32, 169-172.

Kimura, M., Miura, Y., Watanabe, A., Katoh, A., Haraguchi, H. (1991). Methane emission from paddy field (part 1). Effect of fertilization, growth stage and midsummer drainage: pot experiment. *Environmental Science* 4, 265-271.

Kimura, M., Miura, Y., Watanabe, A., Murase, J., Kuwatsuka, S. (1992). Methane production and its fate in paddies. I. Effect of rice straw application and percolation rate on the leaching into subsoil of methane and other soil components. *Soil Science & Plant Nutrition* 38, 665-672.

Kludze, H.K., DeLaune, R.D. (1995). Straw application effects on methane and oxygen exchange and growth of rice. *Soil Science Society of America Journal* 59, 824-830.

Kongchum, M., Bollich, P.K., Hundall, W.H., DeLaune, R.D., Lindau, C.W. (2006). Decreasing methane emission of rice by better crop management. *Agronomy for Sustainable Development* 26, 45-54.

Krüger, M., Frenzel, P. (2003). Effects of N-fertilization on CH_4 oxidation and production, and consequences for CH_4 emissions from microcosms and rice fields. *Global Change Biology* 9, 773-784.

Lemer, J., Roger, P. (2001). Production, oxidation, emission and consumption of methane by soils: A review. *European Journal of Soil Biology* 37, 25-50.

Lemieux, P.M., Lutes, C.C., Santoianni, D.A. (2004). Emissions of organic air toxics from open burning: a comprehensive review. *Progress in Energy and Combustion Science* 30, 1-32.

Lin, L.F., Lee, W.J., Li, H.W., Wang, M.S., Chang-Chien, G.P. (2007). Characterization and inventory of PCDD/F emissions from coal-fired power plants and other sources in Taiwan. *Chemosphere* 68, 1642-1649.

Liu, Y., Yang, M., Wu, Y., Wang, H., Chen, Y., Wu, W. (2011). Reducing CH_4 and CO_2 emissions from waterlogged paddy soil with biochar. *Journal Soils Sediment*s DOI 10.1007/s11368-011-0376-x.

Lu, W.F., Chen, W., Duan, B.W., Guo, W.M., Lu, Y., Lantin, R.S., Wassmann, R., Neue, H.U. (2000). Methane emissions and mitigation options in irrigated rice fields in southeast China. *Nutrient Cycling in Agroecosystems* 58, 65-73.

Ma, J., Li, X. L., Xu, H., Han, Y., Cai, C., and Yagi, K. (2007). Effects of nitrogen fertiliser and wheat straw application on CH_4 and N_2O emissions from a paddy rice field. *Australian Journal of Soil Research* 45, 359-367.

Ma, J., Ma, E., Xu, H., Yagi, K., Cai, Z. (2009). Wheat straw management affects CH_4 and N_2O emissions from rice fields. *Soil Biology & Biochemistry* 41, 1022-1028.

Ma, J., Xu, H., Yagi, K., and Cai, Z. (2008). Methane emission from paddy soils as affected by wheat straw returning mode. *Plant Soil* 313, 167-174.

Majumdar, D. (2003). Methane and nitrous oxide emission from irrigated rice fields: proposed mitigation strategies. *Current Science* 84, 1317-1326.

Mayerhoff, Z.D.V.L., Roberto, I.C., Silva, S.S. (1997). Xylitol production from rice straw hemicellulose hydrolysate using different yeast strains. *Biotechnology Letters* 19, 407-409.

Minamikawa, K., Sakai, N., Yagi, K. (2006). Methane emission from paddy fields and its mitigation options on a field scale. *Microbes and Environments* 21, 135-147.

Minamikawa, K. and Sakai, N. (2006). The practical use of water management based on soil redox potential for decreasing methane emissions from a paddy field in Japan. *Agriculture, Ecosystems and Environment* 116, 181-188.

Naser, H.M., Nagata, O., Tamura, S., Hatano, R. (2007). Methane emissions from five paddy fields with different amounts of rice straw application in central Hokkaido, Japan. *Soil Science and Plant Nutrition* 53, 95-101.

Nayak, D.R., Adhya, T.K., Babu, Y.J., Datta, A., Ramakrishnan, B., Rao, V.R. (2006). Methane emission from a flooded field of eastern India as influenced by planting date and age of rice (Oryza sativa L.) seedlings. *Agriculture Ecosystems and Environment* 115, 79-87.

Neue, H.U. (1993). Methane emission from rice fields: Wetland rice fields may make a major contribution to global warming. *BioScience* 43, 466-473.

Neue, H.U. (1997). Fluxes of methane from rice fields and potencial for mitigation. *Soil Use and Management* 13, 258-267.

Neue, H.U., Lantin, R.S., Wassmann, R., Aduna, J.B., Alberto, M.C.R., Andales, M.J.F. (1994). Methane emission from rice soils of the Philippines. Edición: Minami, K., Mosier, A., y Sass, R. En: *CH4 and N2O, Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources*. NAIES Series 2. Tokyo, Japan, Yokendo Publishers.

Neue, H.U., Roger, P.A. (2000). Rice agriculture: factors controlling emissions. Edición: Khalil, M. A. K. En: *Atmospheric Methane: Its Role in the Global Environment*. Pag. 134-199.

Neue, H.U., Wassmann, R., Lantin, R.S. (1995). Mitigation option for methane emissions from rice fields. Edición: Peng, S., Ingram, K. T., Neue, H. U., y Ziska, L. H. En: *Cllimate Change and Rice*. Pag. 136-144. Germany, Springer-Verlag Berlin Heldelberg.

Niladevi, K.N., Sukumaran, R.K., Prema, P. (2007). Utilization of rice straw for laccase production by Streptomyces psammoticus in solid-state fermentation. *Journal of industrial microbiology and biotechnology* 34, 665-674.

Okasha, F. (2007). Staged combustion of rice straw in a fluidized bed. *Experimental Thermal and Fluid Science* 32, 52-59.

Pütün, A.E., Apaydin, E., Pütün, E. (2004). Rice straw as a bio-oil source via pyrolysis and steam pyrolysis. *Energy* 29, 2171-2180.

Rath, A. K., Swain, B., Ramakrishan, B., Panda, D., Adhya, T. K., Rao, V. R., and Sethunathan, N. (1999). Influence of fertilizer management and water regime on methane emission from tropical rice fields. *Agriculture, Ecosystems and Environment* 76, 99-107.

Reddy, N., Yang, Y. (2006). Properties of High-Quality Long Natural Cellulose Fibers from Rice Straw. J*ournal of Agricultural and Food Chemistry* 54, 8077-8081.

Rodríguez, A., Moral, A., Serrano, L., Labidi, J., Jiménez, L. (2008). Rice straw pulp obtained by using various methods. *Bioresource Technology* 99, 2881-2886.

Saito, T., Miura, Y., and Yokoi, N. (2006). Methane and nitrous oxide emissions and rice growth as influenced by water regimes of the paddy field. *Abstract of the Annual Meeting of the Japanese Society of Soil Science and Plant Nutrition* 52, 190.

Sass, R.L., Fisher, F.M., Wang, Y.B., Turner, F.T., Jund, M.F. (1992). Methane emission from rice fields: The effect of floodwater management. *Global Biogeochemical Cycles* 6, 249-262.

Schütz, H., Holzapfel-Pschorn, A., Conrad, R., Rennenberg, H., Seiler, W. (1989). A 3-year continuous record on the influence of daytime, season and fertilizer treatment on methane emission rates from an Italian rice paddy. J*ournal of Geophysical Research* 94, 16405-16416.

Schütz, H., Schroder, P., Rennenberg, H. (1991). Role in plant regulating the methane flux to the atmosphere. Edición: Sharkey, T. D., Holland, E. A., y Mooney, H. A. En: *Trace Gas Emissions by Plants*. Pag. 29-63. San Diego, Academis Press.

Setyanto, P., Makarim, A.K., Fagi, A.M., Wassmann, R., Buendia, L.V. (2000). Crop management affecting methane emissions from irrigated and rainfed rice in Central Java (Indonesia). *Nutrient Cycling in Agroecosystems* 58, 85-93.

Setyanto, P., Rosenani, A.B., Boer, R., Fauziah, C.I., Khanif, M.J. (2004). The effect of rice cultivars on methane emission from irrigated rice fields. *Indonesian Journal of Agricultural Science* 5, 20-31.

Setyanto, P., Rosenani, A.B., Makarim, A.K., Fauziah, C.I., Bidin, A., Suharsih (2002). Soil controlling fators of methane gas production from flooded rice fields in Pati district, Central Java. *Indonesian Journal of Agricultural Science* 3, 1-11.

Singh, J.S., Singh, S., Raghubanshi, A.S., Singh, S., Kashyap, A.K. (1996). Methane flux from rice/wheat agroecosystem as affected by crop phenology, fertilization and water level. *Plant and Soil* 183, 323-327.

Singh, S.N., Tyagi, L., Tiwari, S. (2009). Attenuanting methane emission from paddy fields. Edición: Singh, S. N. En: *Climate Change and Crops*. Germany, Springer-Verlag Berlin Heidelberg.

Takai, Y., Asami, T. (1962). Formation of methyl-mercaptan in paddy soils. *Soil Science & Plant Nutrition* 8, 40-44.

Tanji, K.K., Gao, S., Scardaci, S.C., Chow, A.T. (2003). Characterizing redox status of paddy soils with ncorporated rice straw. *Geoderma* 114, 333-353.

Torigoe, K., Hasegawa, S., Numata, O., Yazaki, S., Matsumaga, M., Boku, N., Hiura, M., Ino, H. (2000). Influence of emission from rice straw burning on bronchial asthma in children. *Pediatrics International* 42, 143-150.

Vancura, W. and Hovadik, A. (1965). Root exudates of plants. II. Composition of root exudates for some vegetables. *Plant Soil* 22[1], 21-32.

Vibol, S. and Towprayoon, S. (2010). Estimation of methane and nitrous oxide emissions from rice field with rice straw management in Cambodia. *Environmental Monitoring Assessment* 161, 301-313.

Wang, B., Xu, Y., Wang, Z., Li, Z., Ding, Y., Guo, Y. (1999). Methane production potentials of twenty-eight rice soils in China. *Biology and Fertility of Soils* 29, 74-80.

Wang, M., Li, J. (2002). CH_4 emission and oxidation in Chinese rice paddies. *Nutrient Cycling in Agroecosystems* 64, 43-55.

Wang, Y., Hu, C., Zhu, B., Xiang, H., and He, X. (2010). Effects of wheat straw application on methane and nitrous oxide emissions from purplish paddy fields. *Plant Soil Environment* 56[1], 16-22.

Wang, Z.P., Lindau, C.W., DeLaune, R.D., Patrick, W.H. (1992). Methane production from anaerobix soil amended with rice straw and nitrogen fertilizers. *Fertilizer Research* 33, 115-121.

Wang, Z.Y., Xu, Y.C., Li, Z., Guo, Y.X., Wassmann, R., Neue, H.U., Lantin, R.S., Buendia, L.V., Ding, Y.P., Wang, Z.Z. (2000). A four-year record of methane emissions from irrigated rice fields in the Beijing region of China. *Nutrient Cycling in Agroecosystems* 58, 55-63.

Wassmann, R., Aulakh, M.S., Lantin, R.S., Rennenberg, H., Aduna, J.B. (2002). Methane emission patterns from rice fields planted to several rice cultivars for nine seasons. *Nutrient Cycling in Agroecosystems* 64, 111-124.

Wassmann, R., Lantin, R. S., Neue, H. U., Buendia, L. V., Corton, T. M., and Lu, Y. (2000). Characterization of methane emissions from rice fields in Asia. III. Mitigation options and future research needs. *Nutrient Cycling in Agroecosystems* 58, 23-36.

Wassmann, R., Neue, H.U., Bueno, C., Lantin, R.S., Alberto, M.C.R., Buendia, L.V., Bronson, K., Papen, H., Rennenberg, H. (1998). Methane production capacities of different rice soils derived from inherent and exogenous substrates. *Plant and Soil* 203, 227-237.

Wassmann, R., Papen, H., Rennenberg, H. (1993a). Methane emission from rice paddies and possible mitigation strategies. *Chemosphere* 26, 201-217.

Wassmann, R., Schütz, H., Papen, H., Rennenberg, H., Seiler, W., Aiguo, D., Renxing, S., Xingjiang, S., Mingxing, W. (1993b). Quantification of methane emissions from Chinese rice fields (Zhejiang province) as influenced by fertilizer treatment. *Biogeochemistry* 20, 83-101.

Watanabe, A., Yamada, H., Kimura, M. (2005). Analysis of temperature effects on seasonal and interannual variation in CH_4 emission from rice-planted pots. *Agriculture, Ecosystems and Environment* 105, 439-443.

Watanabe, A., Yamada, H., Kimura, M. (2001). Effects of shifting growth stage and regulatibg temperature on seasonal variation of CH_4 emission from rice. Global *Biogeochemical Cycles* 15, 729-739.

Xu, Cai, Z.C., Li, X.P., Tsuruta, H. (2000). Effect of antecedent soil water regime and rice straw application time on CH_4 emission from rice cultivation. *Australian Journal of Soil Research* 38, 1-12.

Xu, H., Cai, Z.C., Tsuruta, H. (2003). Soil moisture between rice-growing seasons affects methane emission, production and oxidation. *Soil Science Society of America Journal* 67, 1147-1157.

Xu, H. and Hosen, Y. (2010). Effects of soil water content and rice straw incorporation in the fallow season on CH_4 emissions during fallow and the following rice-cropping seasons. *Plant and Soil* 335, 373-383.

Yagi, K., Minami, K. (1990). Effect of organic matter application on methane emission from some Japanese paddy fields. *Soil Science & Plant Nutrition* 36, 599-610.

Yagi, K., Tsuruta, H., Kanda, K., Minami, K. (1996). Effect of water management on methane emission from a Japanese rice paddy field: Automated methane monitoring. *Global Biogeochemical Cycles* 10, 255-267.

Yagi, K., Tsuruta, H., Minami, K. (1997). Possible options for mitigating methane emission from rice cultivation. *Nutrient Cycling in Agroecosystems* 49, 213-220.

Yan, X., Akiyama, H., Yagi, K., and Akimoto, H. (2009). Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines. *Global Biogeochemical Cycles* 23, 1-15.

Yan, X., Yagi, K., Akiyama, H., Akimoto, H. (2005). Statistical analysis of the major variables controlling methane emission from rice fields. *Global Change Biology* 11, 1131-1141.

Yang, H.S., Kim, D.J., Kim, H.J. (2003). Rice straw–wood particle composite for sound absorbing wooden construction materials. *Bioresource Technology* 86, 117-121.

Yi, Z., Wang, X., Sheng, G., Fu, J. (2008). Exchange of carbonyl sulfide (OCS) and dimethyl sulfide (DMS) between rice paddy fields and the atmosphere in subtropical China. Agricultue, *Ecosystems and Environment* 123, 116-124.

Zhang, A., Cui, L., Pan, G., Li, L., Hussain, Q., Zhang, X., Zheng, J., Crowley, D., (2010). Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China. *Agriculture Ecosystems and Environment* 139, 469-475.

Zhang, G. B., Ji, Y., Ma, J., Xu, H., and Cai, Z. C. (2011). Case study on effects of water management and rice straw incorporation in rice fields on production, oxidation and emission of methane during fallow and following rice seasons. *Soil Research* 49[3], 238-246.

Zhang, R., Li, X., Fadel, J.G. (2002). Oyster mushroom cultivation with rice and wheat straw. *Bioresource Technology* 82, 277-284.

Zhang, R., Zhang, Z. (1999). Biogasification of rice straw with an anaerobic-phased solids digester system. *Bioresource Technology* 68, 235-245.

Zou, J., Huang, Y., and Jiang, J. (2005). A 3-year field measurements of methane and nitous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application. *Global Biogeochemical Cycles* 19, 1-9.

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