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Environmental Impacts of Rice Cultivation

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Abstract

This paper describes the major environmental aspects related to the cultivation of rice. Rice is one of the most important agricultural products and it is cultivated in almost all countries in the world. Its production requires usually large flooded areas. Under these conditions, many greenhouse gases are generated, such as carbon dioxide, methane, nitrogen oxides and its derivatives. Cultivation of rice is responsible by the release of relevant amounts of these gases and contributes decisively to global warming. In this sense, the major points described here are general environmental aspects, the mechanisms of production of greenhouse gases, bioremediation, mitigation using other techniques and possible improvements of the cultivation by fertilizers and chemicals.

Keywords

Rice, Environmental Aspects, Global Warming, Greenhouse Gases

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1. Introduction

It is well documented and recognized that many anthropogenic activities such as deforestation, energy production (especially fossil fuels consumption) and several industrial activities play an important role in global warming [1] [2]. In fact, most of world concerns seem to be associated to modern civilization aspects, such as utilization of vehicles and large-scale production. Probably, much less attention has been devoted to other "natural" sources of global heating. For instance, nowadays agricultural production is responsible for about 10% to 12% of global greenhouse gas (GHG) emissions [3] [4]. A significant part of global warming is derived from the production of gases, collectively known as greenhouse gases (GHG). Probably the most relevant gases responsible by temperature rise are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). These gases, together with other components, such as ammonium (NH_3) and other nitrogen compounds, are usually generated in animal and agricultural activities. Here we will focus on the deleterious effects of gas production due to rice harvesting. For in-

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stance, considering anthropogenic production, about 47% of methane and 58% of N_2O are derived from agricultural practices [5].

Rice is one of the most important sources of food for the world population. Around 3 billion people or about 50% of human population uses rice as food and nutrients source. China is the major producer of rice in the world. In a recent study [6], the release of methane was estimated in this country. In the first place, **Table 1** presents comparison of methane production according to major activities in China. It can be seen that agricultural production of methane is almost the same of energy production.

On the other hand, considering only agricultural activity, as described in **Table 2**, rice cultivation is responsible for about 35.6% of methane generation. In other words, rice production in China renders about 5613.1 Gg of methane yearly.

The atmosphere concentration of methane has more than doubled from the pre-industrial era to nowadays values, varying from around 700 ppb to 1800 ppb [7]. It shows an effect on greenhouse 25 times superior to carbon dioxide [8].

On the other hand, nitrogen dioxides are also generated in rice fields, since nitrogen is an essential nutrient for plants. The use of fertilizer is, of course, a common practice. The effect of nitrogen oxide in global warming is also very important; it is estimated that this gas is 300 times more potent to cause greenhouse effect than carbon dioxide [9]. Furthermore, the emission of nitrogen oxide has risen up to 17% from 1990 to 2005 and this growth tends to be more dramatic due to use of fertilizers [10]. Also in 2005 about 60% of all nitrogen dioxide emissions were due to agricultural production.

2. The Formation of Greenhouse Gases

Greenhouse effect results in global warming and it is currently one of the main environmental concerns. The major gases involved in this phenomenon are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) [11]. It is well known that these gases are extremely important to retain heat in the atmosphere so that the temperature remains within a range of values appropriate for the existence of life [12]. **Table 3** [13] summarizes the main anthropogenic sources and the lifetime in the atmosphere of the main trace gases involved in greenhouse effect.

Table 1. Activities contribution to CH_4 emissions in China.

Activity	%
Agricultural	40.4
Energy	41.9
Waste management	17.7

Table 2. Agricultural activity and its percentage on methane production.

Agricultural activity	%
Enteric fermentation	51.2
Manure management	10.9
Rice cultivation	35.6
Field burning of agricultural residues	2.3

Table 3. Atmospheric trace gases for the significant increase in the greenhouse effect.

	Methane (CH_4)	Nitrous oxide (N_2O)
Main source anthropogenic	Flooded rice cultivation, livestock, fossil fuels, biomass burning.	Fertilizers, land use conversion.
Lifetime in the Atmosphere	10 years	150 years

Adapted from [14].

Among these gases, probably, the most relevant is methane because of the amount released and the activity performed in the absorption of radiation. The annual global emission of methane from rice fields represent 31 - 112 Tg (Tg = 1012 g), which means approximately 5% - 19% of the overall methane emissions [13]. Some studies suggest the influence of factors such as solar radiation, organic fertilization, temperature, plant biomass, crop type, carbon substrate availability and soil types on the methane emissions in flooded rice fields [15] [16]. Recently [17] a study was conducted to assess the dynamics of methane emission in six different types of soil representing the irrigated rice cultivation in southern Brazil. It was suggested that the dynamics and the total quantities of CH_4 emitted are influenced by the type of soil. In a similar study [18] it was found that CH_4 emission is related to the amount of residues in the soil and how they were incorporated to them. Also it seems that anaerobic conditions [19] of the soil soaked stimulate the production and emissions of methane. The oxidation of CH_4 is performed by methanotrophic bacterias in the oxygen zones the ecosystem (water interface-soil and rhizosphere rice). There is evidence [20] that flooded soils are cultivated under conditions conducive to the methanogenesis, due to the high carbon content and low decomposition rate of the biomass in anaerobic conditions. This process is carried out by methanogenic bacteria which have ability to use carbon compounds of low molecular weight for the production of energy. Thus, these bacteria are dependent on other hydrolytic and fermentative bacteria which reduce the molecular weight of the plant compounds. Methane is absorbed by the roots of rice plants [21] with water or gaseous, without the need for water absorption, being emitted to the atmosphere primarily by diffusion through the aerenchyma rice plants and also by gas bubbles as described in **Figure 1**.

Some works [24] [25] describe between 40% and 60% of the total annual N_2O emissions in the ecosystems rice-based in China occurred in the winter season. The production of N_2O occurs when the floodplain soils suffers cycles of wetting and drying, in which the microorganisms actually perform the sequential processes of mineralization-nitrification-denitrification, as presented in **Figure 2**. It is important to note that the nitrification and denitrification processes are microbiological processes that occur in soils that contribute most to the emission of N_2O.

According to Gomes 2006 [26], the occurrence of nitrification and denitrification processes are determined by the soil conditions such as O_2 supply, water content, temperature, pH, organic matter, presence of vegetable residues and concentration of NH_4^+ and NO_3^-. In the nitrification process the chemoautotrophic bacteria oxidize NH_4^+ (ammonium) in the soil producing N_2O and NO. Nitrification is regulated by the presence of NH_4^+; NO_2 (nitrite), NO_3 (nitrate), PO_4^{3-} (phosphate), O_2, soil acidity, temperature and water potential. The availability of NH_4^+ is considered a limiting factor in nitrification, which is influenced by mineralization/ immobilization, the presence of plants, cation exchange and dissemination. The N_2O production by biological nitrification occurs

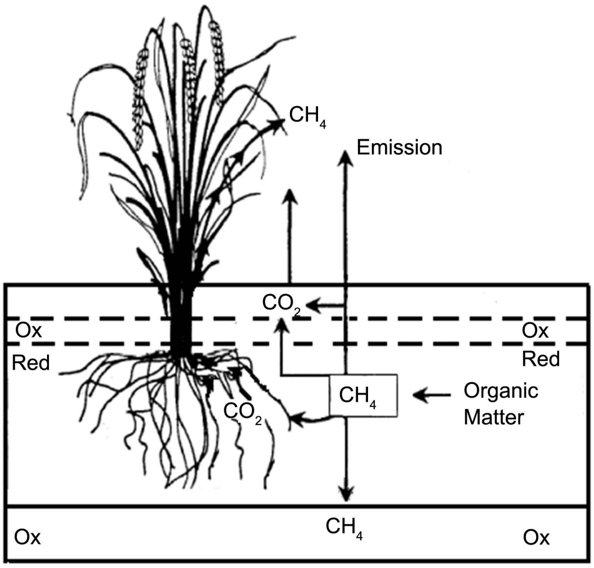

Figure 1. Flowchart adapted production and methane emission in rice fields [22].

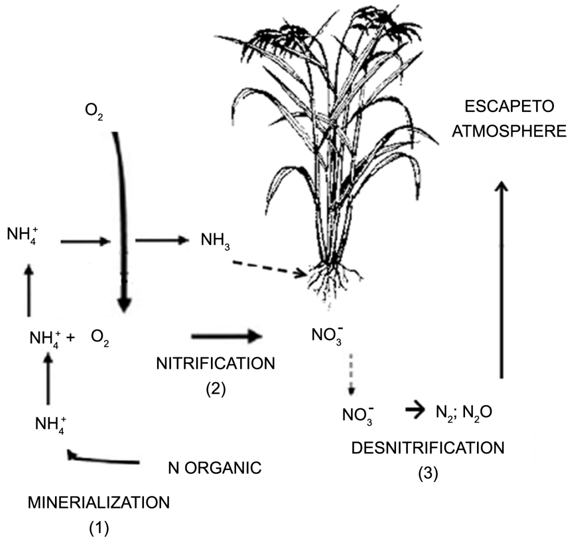

Figure 2. Dynamics of N in flooded soils of rice production (adapted from [23]).

when the bacteria to oxidize NH_4^+ in the absence of O_2, NO_3 use as electron acceptor. Although N_2O production is possible by nitrification, high N_2O emissions have been generally associated with denitrification. In the denitrification process the NO^{2-} and NO_3^- ions are reduced to NO, N_2O or N_2. Cultivation operations include, among other practices, the addition of nitrogenous fertilizer and handling conditions that can cause alternation of oxidation/reduction conditions, which may favor changes in nitrification and denitrification processes, increasing the production and emission of N_2O. According to Dobbie and Smith [27], the use of nitrogen fertilizer, for example, may increase the mineral N content in the soil and as a result, the increase of N_2O emissions from soil. In a recent paper [28] it is described N_2O emissions from the application of two nitrogen fertilizers (ammonium sulfate and urea) at two different doses (100 and 300 kg N ha^{-1}). The authors observed higher soil N_2O emissions for both fertilizers when applying 300 $kg \cdot ha^{-1}$. On the other hand, a recent study [29] reported that N_2O emissions were positively correlated with some variables such as the concentration of O_2 in the soil, the groundwater and rainfall, indicating that soil moisture/aeration and availability of C were the main drivers for emissions of N_2O. The growing world population implies an increase in food production. However, the environmental aspects, such as impacts to the environment must be considered when choosing the type of food cultivation. In feed, rice plays an important role since it is the source of many important nutrients for human beings.

3. Mitigation of Methane from Paddy Wetland: Management Strategies

Rice crop present a different behavior if compared to other common plants; rice can even grow in soil without oxygen at root level. Organic matter is completely converted to CO_2 in high-fertility soil through aerobic pathway, whereas in low-fertility soil only 7% of CO_2 is produced by anaerobic pathways. Soil microorganisms require electron acceptor, usually oxygen, in their chemical reactions, especially aerobic respiration. However if oxygen is depleted other electron acceptors available are used in thermodynamically order (according to redox potential): nitrate $\left(NO_3^-\right)$, Mn (IV), Fe (III) and sulfate $\left(SO_4^{2-}\right)$ [30] [31] also in a concentration cutoff value (**Table 4**).

Methane is produced strictly in anaerobic environment where the redox potential is lower than −200 mV [32] essential condition to methanogenic bacteria starting their activities. These bacteria are strictly anaerobic, such condition is achieved when inorganic nutrients are reduced and organic matter acetate is converted in CO_2 and CH_4; other bacteria group oxidizes H_2 by using CO_2 which is reduced to CH_4 [33].

Rice cultivation generally takes place in irrigated fields to maximize crop yields but constant water supply stimulates anaerobic soil environment formation which augments the CH_4 emissions [34] In fact, rice paddy is the primary anthropogenic source of methane, accounting 11% of the total CH_4 anthropogenic emissions [35].

Methane emission may be affected by different factors: physiological characteristic of rice cultivars (varieties),

Table 4. Concentration cutoff value of electron acceptors according to next most thermodynamically favorable electron accepting process.

Species	Cutoff value (μM)
O_2	0.5
NO_3^-	5
Mn (IV)	0.9
Fe (III)	8
SO_4^{2-}	1000

application of both organic (manure) and inorganic fertilizers, water management, soil physicochemical conditions, soil and air temperature, compositions and activity of soil microorganisms.

Mitigation strategies to CH_4 emission from rice paddies must be farm and eco-friendly, cost-effective without depleting crop yields. At farm level, some approaches (strategies) may arise: management of water, inorganic inputs and selecting rice cultivars [36] [37].

Methane may be partially oxidized in the rhizosphere converted into CO_2 by aerobically oxygen released from plant roots or anaerobically by any electron acceptor available in soil. In this sense, methanogenesis in soil could be inhibited by presence of electron acceptors such as, nitrate, Mn (IV), Fe (III) and sulfate provided by inorganic fertilization or input. Nitrogen-based fertilizers are commonly applied in rice cultivation to enhance crop yields which increases carbon supply for methanogens [38] and provides larger aerenchymal pathway to methane transport from soil to the atmosphere [39] [40]. But nitrogen-based fertilizers also stimulates the growth and activity of methanotrophs (CH_4 oxidizing bacteria) inducing to a methane emission [41] [42]. The effect of nitrogen fertilizers may vary according to form and amount, mode and time of application, also the effects are not consistent (contrasting effects) they range from stimulation, neutral and inhibition.

Emission of methane during the first crop season CH_4 with NH_4^+ and NO_3^- ranged 1.2 - 2.6 and 8.3 - 8.8 g CH_4 m^{-2} respectively for both rice varieties. In second crop season it was observed intensification on CH_4 emission vales ranges were 34.3 - 36.7 and 36.6 - 58.6 g CH_4 m^{-2}. Methane emission rates from the NO_3^- amended plots were 1.5- - 3.7-fold higher than NH_4^+ amended plots during the growth period. The authors explain a higher inhibition effect of CH_4 emission by ammonium sulfate rather than potassium nitrate due to easily leaching of nitrate from soil during the rainy season (period) in Chia-Yi County, Taiwan. In this study a non-fertilizer field was used as control, and then a comparison to reducing CH_4 emission effect was not possible.

In this study methane emission was monitored over 4 years in a paddy rice field with typical Chinese water management (midseason aeration for a few days instead of continuous flooding) with nitrogen addition rates of 0, 150 and 250 kg N ha^{-1} (urea plus ammonium phosphate). The preliminary addition of 150 kg N ha^{-1} presented a negative effect compared to no-nitrogen amendment. It was observed average emission decreased of 38% and 49% in 150 and 250 kg N ha^{-1}, respectively. Considering that addition rate of 250 kg N ha^{-1} is already applied in some parts of China, the authors expect that this rate could be pronounce to others sites in China as an effective management of methane emission reduction and increasing of rice crop yields [43]. In a recent works [44] [45], it was not observed a substantially methane emission reduction when nitrogen input changed from 150 to 250 kg N ha^{-1} or more.

On the other hand [46], the contrasting effects on CH_4 mitigation by N-fertilizers could be related to nitrogen rate input. At low levels of nitrogen, great part is uptake by plants and the remaining nitrogen in soil is insufficient to oxidizing CH_4 or to inhibit methanogens activity, so in this scenario methane emission is increased. On the other hand (In opposition), when higher level of N-fertilizer is applied (range 100 - 200 kg N ha^{-1}) the excess of nitrogen in soil may promote net effect in mitigation of methane emission

Although methane emission can be reduced by nitrogen-fertilizer management, this process is accompanied by a high NO_2 emission, which has a 296 times higher GWP (global warming potential) than CO_2 and 12 times larger than CH_4 [14]. However NO_2 emission is not the scope of this review. Ferric iron or Fe (III) is considered major soil characteristic regulating CH_4 emission from rice soils [47] Methane emission is suppressed by enhancing the activity of iron reducing bacteria and inhibiting the activity of methanogens for the common electron donor. According to Silva et al. while inorganic nutrients (electron acceptors) are available (attainable), like

Fe (III), Mn (IV) and Mn (III), the organic matter using is limited which reduce methane emission.

In a labor scale [48] could observe a net reduction of methane emission of 43% and 84% by addition of 15 and 30 g of ferrihydrate /kg of soil over 143 days during growth and harvest period of rice in beakers. When this assay was applied in rice paddy field, [49] the 1.58 kg of ferrihydrate supply into 2 × 2 m plot could mitigate 50% of methane emission in comparison with a no-Fe (III) supplied area.

Ferric hydroxide and ferrihydrite were used as Fe (III) source in in the field treatment over the paddy rice-winter wheat rotation cycle. The Fe (III) fertilizer was applied at the rate of 4.0 and 8.0 $t \cdot ha^{-1}$, representing medium (Fe-M) and high (Fe-H) application levels in the rice based soils of Southeast China, respectively. Compared with the control, Fe (III) fertilization decreased CH_4 by 27% and 44% for the Fe-M and Fe-H plots, respectively. Besides mitigation CH4 emission from Fe (III) amended soil observed increased in rice crop yield, suggesting win-win management approach [50].

Industrial by-products with high concentration of active iron (Fe) was applied in rice paddy fields (China) in order to evaluate the mitigation potential of steel slag fertilizer in a range of 2 - 8 Mg per ha. In this study was observed an overall decrease CH_4 emission ranging from 26.6% to 49.3% [51].

The addition of sulfate-based fertilizers reduces methane emissions once sulfate reducing bacteria will compete with methane producing bacteria for same substrate. The methane emission from plots amended with 6.66 tons ha^{-1} gypsum was reduced by 55% - 70% compared to non-amended plot [52]. Similar mitigation methane emission was also observed [53] but when phosphogypsum was applied CH4 emission reduced only 50% at a higher level of supplementation (10.0 $t \cdot ha^{-1}$). Linquist and coworkers concluded that mitigation of CH_4 emission is a sulfate rate linear regression, *i.e.*, when there is an increase in sulfate rate is observed a decrease in methane emission.

4. Influence of Chemicals on Gas Production

Nitrification inhibitors (NI) are used to decrease emission of N_2O. The ammonia monooxygenase (AMO) is one enzyme involved in the oxidation of NH_4^+ to NO_3^- in soils [54]. Different nitrification inhibitors of nitrous oxide (N_2O) were studied in one experiment with four treatments: (a) pearled urea; (b) urea þ dicyandiamide (DCD); (c) urea þ Nimin; (d) þ urea Karanjin. CH_4 emission was significantly higher with applications of DCD and Karanjin during the rainy and dry season, respectively. N_2O emission was inhibited with Nimin application more significantly during the rainy and dry seasons (69% and 85% respectively). Applying Nimin increases methanotrophic bacterial population in the soil, and this increase may be related to the low emission of CH_4. In this study it was concluded that, with Nimin and Karanjin, there was a decrease in soil denitrification [55].

Another experiment was conducted to study the effect of the joint application time of hydroquinone as urease inhibitor (HQ) and dicyandiamide as a nitrification inhibitor (DCD) in N_2O emissions in rice fields. These results indicate more efficient inhibition on N_2O emission registered to HQ and DCD applied with fertilizer at tillering stage [56].

The impact of the nitrification inhibitor in rice production, 2-chloro-6 (trichloromethyl) pyridine (CP), was studied using five treatments: CK (no N applied), N180 and N240 and their counterparts N180 + CP and N240 + CP (N use plus CP). The use of 180 $kg \cdot ha^{-1}$ N with CP and the use of 240 $kg \cdot ha^{-1}$ N without CP resulted in the same yield. Despite the increase in NH_3 volatilization with CP, and the consequent increase in indirect emissions of N_2O, it is estimated that CP has led to an overall decrease in global warming potential [57].

Use of two nitrification inhibitors was studied, viz., S-benzylisothiouronium butanoate (SBTbutanoate) and mometasone S-benzylisothiouronium (SBT-furoate) benzylisothiouronium furoate (SBT-furoate). The nitrification inhibitors used in the study increased yield and decreased global warming potential in relation to the treatment of urea [58].

A four-year field campaign was held in the Yangtze River Delta 2004-2007 to assess the effects of more $NH_4H_2PO_4$ urea application on CH_4 emissions in rice cultivation. For addition rate of 250 kg of N Ha^{-1}, CH_4 emissions have been significantly reduced [59].

Wastewater disposal of livestock in paddy fields is a practical treatment adopted by some producers. The influence of such waste water at planting and N_2O emissions was studied. Emissions of N_2O cumulative varied to N750, the N_2O emitted during the final draining, corresponded for 80% of cumulative emissions of N_2O [60].

Influence of ammonia on the application of N_2O emissions was also evaluated. The results revealed a trade-off between CH_4 and N_2O emissions influenced by the application of urea-based fertilizers, *i.e.*, the nitrogen fertilization reduced. Total CH_4 and N_2O, expressed in carbon dioxide equivalents, were affected by rate of addition of nitrogen, with minimal emissions occurring at 250 kg·ha^{-1} [61].

A meta-analysis was performed to determine the effects of treatment medium management practices, both CH_4 and N_2O in rice cultivation. Low inorganic fertilizer N rates increased CH_4 emissions by 18% relative to when no N fertilizer was applied, while high N rates decreased CH_4 emissions by 15%. Replacing urea with ammonium sulfate at the same, N rate significantly reduced CH_4 emissions by 40%, but might increase N_2O emissions. Dicyandiamide led to lower emissions of both CH_4 and N_2O. When compared to inorganic N fertilizers, farmyard manure (FYM) increased CH_4 emissions and the green manure (GrM) Sesbania by 192% [62].

An assessment of the effects of different types of manure about CH_4 and N_2O was performed. The concentration of Zn and Cu in rice and the nitrate content in drainage water were evaluated. The experiment included the following treatments: (a) anaerobically digested sludge cattle (ADCS); (b) ADCS filtered to remove the coarse fraction of soil organic matter; (c) anaerobically digested sludge pig (ADPS); (d) chemical fertilizers (CF). The application rate was 30 mg NH_4-N_2. Different amounts of C were added to fertilization: C 725 m^2 on ADCS, 352 g·m^{-2} in ADCS filtered, and 75 g·m^{-2} in ADPS. This study suggests that ADPS, containing minor amounts of C than ADCS can be used as an organic fertilizer in paddy field showing environmental impacts similar to chemical fertilizers (CF) [63].

Another field experiment was conducted to investigate the effect of biochar at doses of 0, 10 and 40 t·ha^{-1} in rice productivity and CH_4 and N_2O with or without nitrogen fertilizer on a rice plantation. Soil CH_4 emissions total C were increased in soils treated with biochar to 40 t·ha^{-1} compared to treatments without biochar and with or without nitrogen fertilization, respectively. The results showed that biochar significantly increased rice production and reduction of N_2O emissions, but increased the total CH_4 emissions [64].

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