NITROUS OXIDE EMISSION AND NITROGEN UPTAKE AFFECTED BY SOIL AMENDMENT AND NEMATICIDE IN RAINFED RICE SOILS AT CENTRAL JAVA

Emisi Dinitrogen Oksida dan Serapan Nitrogen dari Pemberian Bahan Pembenah Tanah dan Nematisida pada Tanah Sawah Tadah Hujan di Jawa Tengah

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ABSTRACT

Rice cultivation is one of the anthropogenic sources of nitrous oxide (N²O) emission that is produced by microbiological nitrification-denitrification processes. Incorporating soil amendment in rainfed rice soil attempted to increase soil productivity, while nematicide application aimed to maintain root growth system. Incorporating soil amendment and nematicide application are predicted to suppress N₂O production in lowland rice. The objective of this research was to study the interaction of soil organic amendment and nematicide on N₂O emission and nitrogen uptake from rainfed lowland rice soils. A field experiment was conducted in rainfed lowland rice soils during 2010/2011 wet season (direct seeded rice) and 2011 dry season (transplanted rice). The 3 x 3 factorial trial was arranged in a randomized completely block design with three replications. The first factor was soil amendment consisted of without rice straw, fresh rice straw and composted rice straw. The second factor was nematicide application consisted of without nematicide, neemcake and carbofuran. Variables measured were N₂O flux, rice grain yield and nitrogen uptake. Incorporation of fresh and composted rice straws reduced N₂O flux about 49.2% and 59.9% in transplanted rice, and 32.9% and 28.2% in direct seeded rice, respectively. The neemcake application reduced N₂O emission about 44-50%, while carbofuran application decreased N₂O emission by 23-35%. Neemcake has a good potential as nitrification inhibitor of N₂O emission, so the neem trees have a prospect to be cultivated intensively. The reduction of N₂O emission was effective in direct seeded rice system with the application of neemcake and fresh rice straw, however, in transplanted rice system it was effective with neemcake and composted rice straw applications.

[Keywords: Nitrous oxide emission, nitrogen uptake, rainfed lowland, soil amendment, nematicide]

ABSTRAK

Budi daya padi sawah merupakan salah satu sumber antropogenik emisi dinitrogen oksida (N₂O) yang dihasilkan dalam proses nitrifikasi dan denitrifikasi. Pemberanan bahan pembenaan tanah ke dalam tanah sawah tadah hujan bertujuan untuk meningkatkan produktivitas tanah, sedangkan pemberian nematisida untuk mempertahankan pertumbuhan akar. Pemberanan bahan pembenaan tanah dan pemberian nematisida diduga dapat menekan pembentukan N₂O di lahan sawah. Tujuan penelitian ini adalah untuk mengetahui pengaruh pemberian bahan pembenaan tanah dan nematisida terhadap emisi N₂O dan serapan nitrogen pada tanaman padi sawah tadah hujan. Percobaan dilaksanakan di lahan sawah tadah hujan pada musim hujan 2010/2011 (padi gogorancah) dan musim kemarau 2011 (padi walik jerami). Percobaan faktorial 3 x 3 disusun dalam rancangan acak kelompok dengan tiga ulangan. Perlakuan faktor pertama adalah bahan pembenaan tanah yang terdiri atas tanpa jerami padi, jerami segar, dan jerami melapuk. Perlakuan faktor kedua adalah pemberian nematisida yang terdiri atas tanpa nematisida, tepung mimba, dan karbofuran. Peubah yang diukur meliputi flux dinitrogen oksida, hasil gabah, dan serapan nitrogen. Pemberanan jerami segar dan melapuk menurunkan flux N₂O masing-masing 49,2% dan 59,9% pada padi walik jerami, dan 32,9% dan 28,2% pada padi gogorancah. Pemberian tepung mimba menurunkan emisi N₂O sebesar 44-50%, sedangkan pemberian karbofuran mengurangi emisi N₂O 23-35%. Tepung mimba potensial sebagai bahan penghambat nitrifikasi untuk menurunkan emisi N₂O sehingga tanaman mimba mempunyai prospek untuk dibudidayakan secara intensif. Penurunan emisi N₂O efektif pada padi gogorancah dengan pemberian tepung mimba dan jerami segar, namun pada padi walik jerami yang efektif adalah pemberian tepung mimba dan jerami melapuk.

[Kata kunci: emisi dinitrogen oksida, serapan nitrogen, sawah tadah hujan, pembenaan tanah, nematisida]

INTRODUCTION

In Central Java, Indonesia, rainfed rice field covers about 30% of the one million ha of rice areas. The typical rainfed cropping system in Indonesia is a dry direct seeded rice in early wet season followed by...
transplanted rice with minimum tillage in late wet season. The average yield of direct seeded rice (DSR) is 3.5-6.5 Mg ha\(^{-1}\), while that of transplanted rice (TPR) is 1.2-3.0 Mg ha\(^{-1}\) (Boling et al. 2004). The low and unstable rainfed rice yield can be attributed to water stress, nutrient deficiency, pest infestation including nematode, or a combination of these factors. Incorporation of soil amendment such as crop residues and manure is an attempt to improve soil and crop productivity, while application of nematicide is to maintain better root growth of rainfed rice.

The alternate wet-dry soil condition under rainfed rice system influences the magnitude of nitrous oxide (N\(_2\)O) emission. Rice cultivation is a source of atmospheric methane (CH\(_3\)) and nitrous oxide (N\(_2\)O) and as a potential sink for carbon. The N\(_2\)O is produced in soil either from nitrification process under aerobic condition or from denitrification process under anaerobic condition (Majumdar 2003). The N\(_2\)O in soil is produced by microbial nitrification process during oxidation of ammonia to nitrate and nitrate reduction. Nitrifier bacteria (Nitrosomonas and Nitrobacter) which are chemoautotrophic bacteria play a role in nitrification-denitrification processes and N losses from rice field (Minami and Fukushi 1984). Under reductive soil condition, anaerobic facultative bacteria of denitrifier change nitrate to N\(_2\)O and N\(_2\) (Klemedtson et al. 1988). The microbial processes that regulate N\(_2\)O emission from rice cultivation are controlled by soil ammonium (NH\(_4^+\)) and nitrate (NO\(_3^-\)), and moisture availability (Jetten 2008). Nitrate is quite unstable in flooded soils which will be lost as N\(_2\)O and N\(_2\) via denitrification in some days after flooding (Ladha et al. 1997). Denitrification produces N\(_2\)O in anaerobic soil conditions, however, it could also take place with existence of oxygen. Some denitrification bacteria use O\(_2\) and NO\(_3^-\) simultaneously as electron acceptor (Klemedtson et al. 1988).

The N\(_2\)O emission was accounted for about 30% of the total national green house gas (GHG) emission from agriculture in 2005 (80,179 Gg CO\(_2\)-eq), which was lower than CH\(_4\) emission contribution (67%) (Ministry of Environment 2010). The agricultural soils contribute N\(_2\)O as much as 0.2-2.1 Tg N\(_2\)O worldwide (Hansen and Bakken 1993). The atmospheric N\(_2\)O concentration is reported to increase with the rate of 0.25% per year (Snyder et al. 2009). The lifetime of N\(_2\)O in atmosphere is relatively longer than that of methane gas, and its global warming potential is 250-310 times higher than that of CO\(_2\) (Abao et al. 2000).

Application of soil organic amendments to annual crops generally increases denitrifier activity and N\(_2\)O emission (Meijide et al. 2009). Rice straw is one of organic amendments that is excessively available in rainfed rice ecosystems. Incorporation of rice straw into the soil returns most of the nutrient and helps to conserve soil nutrient reserves in the long term. About 40% of N taken up by rice remains in vegetative plant parts at crop maturity (Dobermann and Fairhurst 2002).

Rice straw management in rainfed rice field could affect pattern and magnitude of N\(_2\)O emission (Xiong et al. 2007). According to Meijide et al. (2009), higher emission of N\(_2\)O from manure or crop residues is attributed to more anoxic conditions produced by the stimulation of denitrification and to the supply of readily available C, a substrat for denitrification, so that it favors for generating N\(_2\)O.

Pesticidal materials could function as nitrification inhibitors that are often used to increase N fertilizer use efficiency (Rao 1994) and decrease NO\(_3^-\) and N\(_2\)O losses from denitrification process (Chen et al. 2008). According to Kusmaraswamy et al. in Sahrawat (2004), carbamate pesticides such as carbofuran (2,3-dihydro-2,2-dimethyl-7-benzophuranil methylcarbamate) could be used as nitrification inhibitor and controlling plant pests. The commercial carbofuran is used as nematicide in food crops to maintain root growth. Some natural materials such as neem tree (Azadirachta indica A Juss) seed and its extract have been used as a biological nematicide for food crops and as a nitrification inhibitor. Neem seeds contain the active fractions such as azadirachtin, meliantriol, salamin and nimbin (Vijayalakshmi et al. 1995) which potentially reduce N\(_2\)O generation (Third et al. 2010). The azadirachtin in neem seeds and carbofuran can be expected to have a similar effect on suppressing N\(_2\)O emission. Neem seed could be regarded as a cheap nematicide and more friendly to the environment than carbofuran that could contaminate rice ecosystem.

Neem trees are found easily in Java and Bali (Ambarwati 2007) and can grow in many locations with various soil types such as clay soil, saline soil, flooded soil and unfertile soil. Neems in India are used for medicine, botanical studies, mass propagation techniques, food preservation, pollution prevention, poultry and cattle feed, fertilizer, soil conservation, pharmacology, etc. (Puri 1999).

Rice crops absorb nitrogen in the forms of ammonium (NH\(_4^+\)) and nitrate (NO\(_3^-\)). N uptake is controlled by availabilities of NH\(_4^+\) and NO\(_3^-\) in soil, N loss from soil-crop system including N\(_2\)O in denitrification process and root ability to absorb N (Yamakawa et al. 2004).
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Information on the effect of soil organic amendment and nematicide application on \( \text{N}_2\text{O} \) emission in rainfed rice field is relatively limited. The objective of this research was to determine the effects of soil amendment and nematicide application on \( \text{N}_2\text{O} \) emission and N uptake from rainfed rice field.

**MATERIALS AND METHODS**

**Experimental Site**

The experiment was conducted in intensive rainfed rice areas in Jakenan Subdistrict of Pati District, Central Java during 2010/2011 wet season (November 2010 to March 2011) and 2011 dry season (March to June 2011). The experimental site was located at altitude of 15 m above sea level, 17 km south of north coast of Central Java (11°10' E and 6°45' S). The average annual rainfall at the site was lower than 1,500 mm (Boling et al. 2004). The average daily maximum temperature was 31.7°C and the average minimum temperature was 23.5°C. Solar radiation was low (13 MJ m\(^{-2}\) d\(^{-1}\)) from December to February and high (18 MJ m\(^{-2}\) d\(^{-1}\)) from August to October. The soil was classified as Vertic Endoaquepts with pH-H\(_2\)O of 5.6 and contained low total N (0.3 mg g\(^{-1}\)) and low organic C (3.2 mg g\(^{-1}\)).

**Experimental Design**

The factorial trial of 3 x 3 was arranged in randomized complete block design with three replications. The first factor was soil organic amendment (without soil amendment, fresh rice straw 5 t ha\(^{-1}\) and composted rice straw 5 t ha\(^{-1}\)). The second factor was nematicide (without nematicide, neemcake 20 kg ha\(^{-1}\) and carbofuran 20 kg ha\(^{-1}\)). Organic amendments of rice straw were incorporated during soil tillage, while nematicides were applied three times coincided with N fertilizer application.

Under direct seeded system in 2010/2011 wet season, rice seeds were planted using dibble in plots of 4 m x 5 m with spacing of 20 cm x 20 cm. Under transplanted system in 2011 dry season, the two-week rice seedlings of Ciherang variety were transplanted from seedbed. The direct seeded rice was planted on November 19, 2010 and harvested on March 8, 2011, while transplanted rice was transplanted on March 18, 2011 and harvested on June 10, 2011.

After incorporating organic amendment, land was incubated for two weeks before transplanting. Nematicide materials were grinded, sieved and then applied together with N fertilizer. Recommended inorganic fertilizers were applied at the rates of 120 kg N, 45 kg P\(_2\)O\(_5\), and 60 kg K\(_2\)O per hectare in the forms of urea, SP 36 and KCl, respectively. The N-urea fertilizer was applied in three splits, namely 1/3 before planting, 1/3 at 40 days after germination (DAG) and 1/3 at 55 DAG. SP36 fertilizer was applied before planting and KCl was applied in two splits, namely 1/2 before planting and 1/2 at 55 DAG. The content of N, P and K in rice straw was considered in calculation of inorganic fertilizer requirement. The crop was monitored and controlled intensively for pests, diseases and weeds.

**Data Collection**

Variables observed were \( \text{N}_2\text{O} \), \( \text{NO}_3^- \) and \( \text{NH}_4^+ \) contents in soil, N uptake and rice grain yield. N uptake was calculated from multiplication of N concentration in biomass and biomass weight (grain and straw). Nitrous oxide flux was measured at several crop growth stages, namely active tillering, maximum tillering, panicle initiation, heading and maturity stage. The gas sample was taken using closed chambers from plexiglass material with size of 40 cm (length) x 20 cm (width) x 20 cm (height). The chambers were laid in soil surface between rice hills.

The gas samples were taken in four time intervals of 10, 20, 30 and 40 minutes during early morning (07.00-09.00 a.m.) using 10 ml polypropilen syringes. The syringes were coated with aluminum foil to reduce sunny radiation during gas sampling. At gas sampling, air temperature and chamber headspace were also measured. The gas sample was analyzed using a gas chromatography equipped with electron capture detector (ECD) and Porapak Q column to determine \( \text{N}_2\text{O} \) flux (Jain et al. 2000). The Shimadzu 14A chromatography gas that has been calibrated with high precision (detector 150°C, colomn 100°C, injector 150°C) was used to measure \( \text{N}_2\text{O} \) flux. Nitrous oxide flux was computed following the equation from Lantin et al. (1995).

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E = \frac{dc}{dt} \cdot \frac{V_{ch}}{A_{ch}} \cdot \frac{W_m}{V_m} \cdot \frac{273.2}{273.2 + T}
\]

\[
\frac{dc}{dt} = \text{N}_2\text{O} \text{ rate per time (mole ppb minute}^{-1})
\]

\[
E = \text{N}_2\text{O flux (µg m}^{-2}\text{ minute}^{-1})
\]
\[ V_{ch} = \text{chamber volume (m}^3) \]
\[ A_{ch} = \text{chamber area (m}^2) \]
\[ W_{m} = \text{weight of N}_2\text{O compound (44.02 x 10}^3\text{mg)} \]
\[ V_{m} = \text{volume of N}_2\text{O compound at 1 bar pressure (22.41 x 10}^{-3}\text{m}^3) \]
\[ T = \text{average temperature inside the chamber during gas sampling (°C)} \]

**Data Analysis**

Data were analyzed using analysis of variance to determine treatment effects and least significant difference (LSD) test at the 5% level to evaluate the differences between means.

**RESULTS AND DISCUSSION**

**Dynamics of N\(_2\)O Flux**

In direct seeded rice crop, N\(_2\)O fluxes were high at early rice growth (active tillering) stage and declined until heading or maturity stage (Fig. 1). The high N\(_2\)O flux at early growth stage related with aerobic soil condition due to low rainfall in September-October 2010 (Fig. 2), but became saturated at 30 DAG. Nitrous oxide produced at early rice growth stage might be an intermediate product of nitrification and denitri-

Adequate rainfall in dry soil increases N\(_2\)O emission due to increased N input from rain into organic N pool in the soil (Johnson *et al.* 2007). Decomposition rate of organic matter in aerobic soils generally takes place faster that reduces available carbon and increases electron acceptor requirement during intensive mineralization and reduction of NO\(_3\) to N\(_2\)O (Gold and Oviatt 2005).

Application of nitrification inhibitor reduced N\(_2\)O flux from rainfed rice field with direct seeded rice cropping. The N\(_2\)O flux in plot with neemcake was lower than those with carbofuran and without nematicide. The highest N\(_2\)O flux was found in plot without nematicide followed by plots treated with carbofuran and with neemcake. Nitrous oxide fluxes under direct seeded rice at active tillering, maximum tillering, panicle initiation, heading and maturity growth stages were 0.84-4.12, 0.05-0.50, 0.07-0.19, 0.04-0.22, and 0.03-0.51 µg N\(_2\)O m\(^2\) minute\(^{-1}\), respectively.

The highest N\(_2\)O flux from rainfed rice field occurred at 60 DAG (after panicle initiation stage) in transplanted rice (Fig. 3). The N\(_2\)O increased at early growth stage from active tillering to maximum tillering, and reached the peak at panicle initiation stage. The N\(_2\)O flux declined at crop reproductive growth stage from heading to maturity stage or harvesting time. In transplanted rice crop, N\(_2\)O fluxes at active tillering, maximum tillering, panicle initiation, heading and maturity growth stages were 0.08-1.10, 0.10-0.66, 0.20

![Fig. 1. Dynamics of nitrous oxide fluxes in direct seeded rice crop applied with soil amendments (fresh and composted rice straw) and nematicide, Jakenan, Pati, Central Java, 2010/2011 wet season (November 2010 to March 2011); N1 = first N application, N2 = second N application, N3 = third N application.](image-url)
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-1.38, 0.02-0.14, and 0.10-0.63 µg N\textsubscript{2}O m\textsuperscript{-2} minute\textsuperscript{-1}, respectively. The highest N\textsubscript{2}O flux was found on plots without soil amendment and without nematicide, and it was significantly different from applying rice straw combined with nematicide (Fig. 3).

The highest N\textsubscript{2}O flux at panicle initiation growth stage of transplanted rice seemed attributed to optimal root exudation. Rice roots produce more exudates at early generative growth or panicle initiation stage (Yoshida 1978). Translocation of photosynthate from leaves to roots is optimal at panicle initiation stage and it is translocated partly into rice grains at reproductive growth stage (Yoshida 1978). Root exudates are required by microbes in their metabolism as energy source or substrates in their activities, including denitrifier in anaerobic soil condition.

Root exudate is organic matter which consists of carbohydrate, organic acids and amino acids that are fermented to acetic acid or CO\textsubscript{2} and H\textsuperscript{+}. Some root exudates are used by certain microbes as electron acceptor (Holzapfel-Pschron et al. 1986).
Soil Nitrate Content in Rice Rizhosphere

Potential N₂O emissions from rice field increase if available N for microbial transformation is enhanced through inorganic N fertilization, legume cropping, incorporation of organic fertilizer and plant residues into soil, and mineralization of soil biomass and other soil organic matter. The flooded rice field is ideal habitat for anaerobic facultative bacteria such as denitrifier in releasing N₂O and fixing N₂ that can function well in soil with low oxygen availability (Rao 1994).

Nitrogen availability in soil affected the generation and release of N₂O. The high N₂O fluxes seem to be influenced by nitrate content in rice rizhosphere. Nitrate content was high at panicle initiation stage, namely 45 days after transplanting in transplanted rice or 60 DAG in direct seeded rice (Fig. 4). In direct seeded rice, nitrate content in soil at 25 DAG was higher than that at 45 DAG, so that it contributed to the high N₂O flux at early rice growth stage (Fig. 1). Soil nitrate content is one of key factors that influences denitrification process and N₂O emission from agricultural soils (Xiong et al. 2007). Nitrate is a mobile anion that easily leached into soil reductive layer and used by denitrification bacteria as electron acceptor in producing N₂O gas (Unger et al. 2009).

Nitrous Oxide Emission from Rainfed Rice Soils

Incorporation of rice straw into the soil influenced significantly N₂O emission from rainfed rice field (p < 0.0001). Application of nematicides reduced significantly N₂O emission (p < 0.0001), however, its interaction with soil amendment treatment was only significantly different in direct seeded rice crop (p < 0.001). Nitrous oxide emission in direct seeded rice was higher than that in transplanted rice. The N₂O emissions from transplanted rice ranged from 57 to 320 g ha⁻¹ season⁻¹, whereas from direct seeded rice it ranged from 124 to 485 g ha⁻¹ season⁻¹ (Table 1). The low water availability in early growth stage of direct seeded rice produced a high N₂O compared with that of transplanted rice.

Rice straw application decreased significantly N₂O flux relative to without rice straw application because lignin content in rice straw can inhibit N₂O generation in nitrification and denitrification processes (Dobermann and Fairhurst 2002). The average N₂O flux emissions from plots without rice straw and those treated with fresh or composted rice straw were 242, 123 and 97 g N₂O ha⁻¹ season⁻¹ in transplanted rice, and 316, 212, 227 g N₂O ha⁻¹ season⁻¹ in direct seeded rice, respectively (Table 1). Applications of fresh or composted rice straw reduced N₂O fluxes as much as 49.2% and 59.9% in transplanted rice, and 32.9% and 28.2% in direct seeded rice, respectively. The composted rice straw application reduced N₂O emission higher than the fresh rice straw application in transplanted rice.

Interaction of rice straw and nematicide application reduced significantly N₂O emission. Rice straw application in situ into rice soils generally increased N fixation and reduced denitrification rate and N₂O formation (Vallejo et al. in Meijide et al. 2009). Application of rice straw reduced N₂O release from soil to atmosphere, meaning that it reduced N losses in N₂O form resulted from nitrification-denitrification.

Fig. 4. Soil nitrate content in rainfed rice rhizosphere treated with soil amendment and nematicide on direct seeded rice and transplanted rice, Jakenan, Pati, Central Java, wet season 2010/2011 and dry season 2011: N1 = first N application, N2 = second N application, N3 = third N application.
Application of nematicide materials reduced $\text{N}_\text{2O}$ emission significantly relative to applying nematicide. $\text{N}_\text{2O}$ emission from neemcake treatment was lower than that from carbofuran treatment. Nitrous oxide emissions in treatments without nematicide, and those with neemcake and carbofuran were 209, 117 and 136 g $\text{N}_\text{2O}$ ha$^{-1}$ season$^{-1}$ in transplanted rice, and 332, 167 and 257 g $\text{N}_\text{2O}$ ha$^{-1}$ season$^{-1}$ in direct seeded rice, respectively. Applications of neemcake and carbofuran reduced $\text{N}_\text{2O}$ emissions as much as 44.0% and 34.9% in transplanted rice, and 49.7% and 22.6% in direct seeded rice, respectively (Table 1).

Neem seed is more effective than carbofuran in reducing $\text{N}_\text{2O}$ emission, especially if it is combined with composted rice straw. In this study, neem seeds contained 0.13% tannin that is a compound that could inhibit bacterial activities in nitrification and denitrification processes. Tannin is a polyphenolic organic compound that could be used by fungi of genus *Aspergillus* and *Penicillium*, so that it inhibits *Aspergillus* and other bacterial activities (Rao 1994). Although amino acids are more available in rhizosphere, polyphenolic compound will inhibit activity of some bacterial genera. Commonly found in rhizosphere, namely *Pseudomonas, Achromobacter, Arthrobacter, Azotobacter, Mycobacterium* and *Bacillus*. Among those genera, *Pseudomonas* and *Achromobacter* are the main ones involved in denitrification processes in rice field (Rao 1994).

The lowest $\text{N}_\text{2O}$ emission was found in plot treated with composted rice straw + neemcake, namely 57 ± 8 g $\text{N}_\text{2O}$ ha$^{-1}$ season$^{-1}$ in transplanted rice, and in plot treated with fresh rice straw + neemcake in direct seeded rice (124 ± 6 g $\text{N}_\text{2O}$ ha$^{-1}$ season$^{-1}$). The nitrous oxide emission in treatment of composted rice straw + neemcake was not significantly different from treatment of fresh rice straw + neemcake. Thus, application of rice straw + neemcake reduced effectively $\text{N}_\text{2O}$ emission from rainfed rice field. In plots either without rice straw or with composted rice straw, application of neemcake produced the lowest $\text{N}_\text{2O}$ emission followed by carbofuran application and without nematicide. In plot with fresh rice straw, carbofuran application emitted the lowest $\text{N}_\text{2O}$ followed by neemcake application and without nematicide.

The highest $\text{N}_\text{2O}$ emission was found in plot without nematicide + without rice straw, namely 320 ± 20 g $\text{N}_\text{2O}$ ha$^{-1}$ season$^{-1}$ in transplanted system and 485 ± 14 g $\text{N}_\text{2O}$ ha$^{-1}$ season$^{-1}$ in direct seeded system. The high $\text{N}_\text{2O}$ fluxes were affected by N fertilizer transformation through nitrification and denitrification processes, so that the nitrate produced is ineffective. However, the effect of rice straw incorporation into the soil was not consistent among cropping seasons. Rice straw is an indirect source of C-N availability from rice straw decomposition in anoxic condition. According to Kirk (2000), anaerobic organic matter decomposition produces simple organic acids + amino acids $\text{RCH}_2\text{NH}_2\text{COOH} + \text{NH}_4^+$. Beside that, nitrification inhibitor materials will inhibit the oxidation of $\text{NH}_4^+$ to $\text{NO}_2^-$ and $\text{N}_2$O (Kirk and Kronzucker 2005).
used as substrate in generating and releasing N\textsubscript{2}O gas to atmosphere. According to Meijide \textit{et al.} (2009), application of N fertilizer into irrigated rice field or lowland rice system with high rainfall favors denitrifier that increases atmospheric N\textsubscript{2}O emission.

**Nitrogen Uptake in Rainfed Rice Crops**

The high nitrogen absorbed by rice crop means that external supply of organic and inorganic nitrogen was efficiently used by rice crop such that N losses could be suppressed. Figure 5 shows that N uptake in direct seeded rice was relatively higher than that in transplanted rice because direct seeded rice yielded biomass higher than transplanted rice. Application of rice straw did not generally increase N uptake, however application of nematicide materials tended to increase N uptake in rainfed rice. In transplanted rice, the highest N uptake was found in plot without rice straw + neemcake (93 kg N ha\textsuperscript{-1}), whereas in direct seeded rice the highest N uptake (116 kg N ha\textsuperscript{-1}) occurred in plot with fresh rice straw.

Rice crop absorbs nitrogen in the forms of NH\textsubscript{4}\textsuperscript{+}-N and NO\textsubscript{3}\textsuperscript{-}-N. NH\textsubscript{4}\textsuperscript{+} could be retained on surface of cations exchange complex that could prevent N losses through leaching. Ammonium ion is an important N source in reductive soil, whereas NO\textsubscript{3}\textsuperscript{-} is adsorbed weakly on soil particle so that it is leached easily and diffused to reductive soil layer. Nematicide materials play a role in delaying or inhibiting oxidation of ammonium to nitrate, so that N is stable in NH\textsubscript{4}\textsuperscript{+} form readily available for plants (Ladha \textit{et al.} 1997).

Application of nematicide generally increased N uptake because better root development might be optimal for nutrient absorption. Application of neemcake together with inorganic N fertilizer improved fertilizer application efficiency through increasing N uptake, but it did not increase grain yield (Table 1). According to Ladha \textit{et al.} (1997), from the applied N fertilizer in rice soil, only 20\% is deposited in grains, 12\% in straw, 3\% in roots, 24\% retained by soil and 41\% is lost through volatilization, nitrification-denitrification, run off and leaching. Application of nitrification inhibitor together with N fertilizer aimed to improve N uptake in critical growth stages (Kirk 2000).

Nitrogen uptake is influenced by the magnitude of N-NO\textsubscript{3} and N-NH\textsubscript{4} in the soil. Exchangeable NH\textsubscript{4}\textsuperscript{+} in soil under direct seeded rice cropping was relatively higher than that under transplanted rice cropping (Fig. 6). Soil exchangeable NH\textsubscript{4}\textsuperscript{+} at maximum tillering stage was higher than that at maturity growth stage. Soil exchangeable NH\textsubscript{4}\textsuperscript{+} in transplanted rice ranged from 36 to 109 ppm N-NH\textsubscript{4}\textsuperscript{+} at 45 DAG and 18-74 ppm N-NH\textsubscript{4}\textsuperscript{+} at 95 DAG, whereas in direct seeded rice it ranged from 38 to 135 ppm N-NH\textsubscript{4}\textsuperscript{+} at 45 DAG and from 19 to 78 ppm N-NH\textsubscript{4}\textsuperscript{+} at 95 DAG, respectively.

Application of nematicides generally increased exchangeable NH\textsubscript{4}\textsuperscript{+} in rainfed rice soils (Fig. 6). Nematicide materials either neemcake or carbofuran were effective to control conversion of NH\textsubscript{4}\textsuperscript{+} to NO\textsubscript{2}\textsuperscript{-} and NO\textsubscript{3}\textsuperscript{-}. Nitrification inhibitor materials controlled N\textsubscript{2}O emissions indirectly by preventing NO\textsubscript{3}\textsuperscript{-} accumulation in soil, so that rice crop effectively absorbed N in NH\textsubscript{4}\textsuperscript{+} form.

**Fig. 5.** Nitrogen uptake in biomass of rainfed rice crops at harvesting time treated with soil amendment (fresh and composted rice straw) + nematicide application, Jakenan, Pati, Central Java, wet season 2010/2011 and DS 2011 dry season.
CONCLUSION

Rice straw incorporation into rainfed rice soils significantly reduced nitrous oxide emission from rice soils with a range of 28.2-32.9% in direct seeded rice and 49.2-59.9% in transplanted rice. Application of neemcake or carbofuran significantly reduced N\textsubscript{2}O emissions from rainfed rice soils as much as 49.7% and 22.6% in direct seeded rice and 44.0% and 34.9% in transplanted rice, respectively.

Nitrogen uptake in direct seeded rice was relatively higher than that in transplanted rice and this lead to a higher biomass production in direct seeded rice. N uptake of rainfed rice crops was high when nematicide materials were applied.

Farmers should apply composted rice straw in rainfed rice field to reduce N losses in form of N\textsubscript{2}O and to improve N fertilizer efficiency. Application of natural nematicides such as neemcake is effective as nitrification inhibitor.

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