



Fakultas Pertanian dan Bisnis Universitas Kristen Satya Wacana
Jl. Diponegoro 52-60 SALATIGA 50711 - Telp. 0298-321212 ext 354
email: jurnal.agric@adm.uksw.edu, website: ejournal.uksw.edu/agric

Terakreditasi Kementerian Riset, Teknologi dan Pendidikan Tinggi berdasarkan SK No 200/M/KPT/2020

TECHNOLOGIES TO REDUCE EMISSION OF METHANE AND NITROUS OXIDE IN RICE FIELDS: A BRIEF REVIEW

Anicetus Wihardjaka

Indonesian Research Center for Food Crops, National Research and Innovation Agency,
Cibinong, West Java, Indonesia.
email: awihardjaka@gmail.com

Received: 17 February 2022 | Accepted: 20 September 2022

ABSTRACT

*Climate change caused by increasing anthropogenic greenhouse gas concentrations can threaten food security. Agricultural land is a source of food availability, however it is one source of GHG emissions, especially methane and nitrous oxide. Integration management of land, water, and plants in an integrated manner can be an effort to reduce the impact of climate change. This paper aims to inform the technologies to reduce emissions of methane and nitrous oxide in rice fields. One of the technologies to mitigate greenhouse gas emissions on agricultural land is through the use of natural materials as an inhibitor for the formation of methane and nitrous oxide in the soil due to the content of secondary metabolites in natural ingredients. Natural materials can simultaneously increase nitrogen nutrient uptake and improve crop yields. The methane production in rice fields is suppressed by more than 30% by coconut fiber, turmeric rhizomes, leaf of *Ageratum conyzoides*, and the leaf of *Cosmos caudatus*; while application of *Cosmos caudatus* and *Ageratum conyzoides* can also reduce the production of nitrous oxide more than 20%, respectively.*

Keywords: *natural materials, methane, nitrous oxide, rice fields*

INTRODUCTION

Climate change occurs due to global warming caused by increased concentrations of anthropogenic greenhouse gasses in the atmosphere. The impact of climate change occurs in various sectors, including the agricultural sector. Changes in global climate may affect temperature and moisture, which will directly influence nutrient cycling and availability, and food security (Mosier *et al.*, 2004). The impact of climate change directly has implications for decreasing the production and welfare of farmers, and also indirectly influencing, namely reducing the productivity of food crops and increasing pest and plant disease attacks (Santoso, 2016). The demand for food crops, especially rice, is expected to increase globally by 35% by 2030, and there is a need to increase the global agricultural productivity by 60-110% to provide food security by 2050 (Gorh *et al.*, 2018).

Global GHG emissions are predicted to increase by 35-60% at the end of 2030 (Hussain *et al.*, 2014). Indonesia's attention to climate change is no longer doubted, as indicated by ratifying the Kyoto Protocol to reduce GHG emissions with Law 17/2004 and supporting Paris's agreement with Law 16/2016. The Paris Agreement seeks to prevent an increase in global temperatures by an average of 2°C and seeks to limit temperature increases of 1.5°C above pre-industrial levels. The global mean annual temperature is considerably increasing due to the enhanced greenhouse effect, which is estimated at 1.1 to 6.4°C at the end of the twenty-first century (Hussain *et al.*, 2014). Based on the Intergovernmental Panel on Climate Change (IPCC) report that the increase in average temperature

in Indonesia is included in the group of countries whose temperature increases are around 0.2°C and less than 1°C in the period 1970-2004 (Khudori, 2011). In 2019, Indonesia experienced an average temperature increase of 0.58°C compared to the normal period or the time range of 1981-2010 (Bappenas, 2019). In addition, Indonesia is committed to reducing GHG emissions by 29% independently or 41% with international cooperation in 2030 (KLHK, 2019). The Government has even issued Presidential Regulation 61/2011 concerning action plans for reducing GHG emissions and Presidential Regulation 71/2011 concerning the implementation of greenhouse gas inventories.

The agricultural sector contributes to the national GHG emissions by 13% (MEF, 2018). GHG emissions from the agricultural sector are predicted to increase by around 5% by 2030 (115.86 million tons CO₂-equivalent) without mitigation efforts (KLHK, 2016). The agricultural sector, which plays an important role in food security, is vulnerable to climate change, a source of greenhouse gas emissions, and a potential solution to reducing emissions through mitigation efforts.

One source of anthropogenic GHG emissions in the agricultural sector is rice fields. Rice fields are seen as a major source of methane and nitrous oxide emissions (Haque *et al.*, 2017). Both methane (CH₄) and nitrous oxide (N₂O) are more potent than carbon dioxide (CO₂) in driving climate change. Methane emissions comprise roughly 90% of the global warming potential (GWP) of flooded rice systems, while N₂O makes up the remainder (Brodt *et al.*, 2014). Mitigation technologies are efforts to reduce

greenhouse gas emissions in rice fields which integrate the components of soil, water, plants, and cultivation practices. One of the technologies to mitigate greenhouse gas emissions is the use of agricultural wastes as nitrification and methanogenesis inhibitors.

Natural materials in the form of plant parts and agricultural waste have the potential to be used as nitrification and methanogenesis inhibitors where these materials are abundantly available, inexpensive, safe, easily decomposed, and are renewable. This paper aims to inform the technologies to reduce methane and nitrous oxide emissions in rice fields through utilization of natural materials.

GHGs IN RICE FIELDS

The agricultural sector is a source of GHG production, especially methane (CH_4) and nitrous oxide (N_2O), which comes from rice fields, biomass burning, agricultural land, enteric fermentation, livestock manure management (Mosier *et al.*, 2004; Jugold *et al.*, 2012; Zhang *et al.*, 2020). In the last two decades, concentrations of CH_4 and N_2O in the atmosphere have increased at a rate of 0.9% and 0.3% per year, respectively (Wihardjaka *et al.*, 2011; Piva *et al.*, 2019). CH_4 and N_2O contribute to 25 times and 298 times the greenhouse effect by CO_2 , respectively, and 50% and 60% of greenhouse gases are generated by agricultural activity (Kang *et al.*, 2021). These gasses are important to atmospheric chemistry and the earth's radiative balance because of the long atmospheric lifetimes of CH_4 and N_2O (<“10 years for CH_4 and 120 years for N_2O) and infrared absorption properties in the troposphere (Mosier *et al.*, 2004). Nitrous oxide (N_2O) is a powerful greenhouse gas that

N_2O can lead to ozone depletion in the stratosphere (Du *et al.*, 2022). Annual methane emissions from paddy fields have been estimated at 36 Tg per year (1 Tg = 10^{10} g) which contributes around 15-20% of total anthropogenic methane emissions (Jiang *et al.*, 2013; Lagomarsino *et al.*, 2016). Rice fields contribute about 30 and 11% of global agricultural CH_4 and N_2O emissions, respectively. The GWP of the rice crop is 467 and 169% higher than wheat and maize (Hussain *et al.*, 2014).

Methane is produced from the process of organic matter decomposition in anaerobic soil conditions by involving methanogenic bacteria (Mosier *et al.*, 2004). Methanogen bacteria that are neutrophilically active produce methane in low oxygen soil conditions, redox potential less than -150 mV, and available organic substrates (Neue, 1993; Sahrawat, 2004; Kang *et al.*, 2021). Methanogenic bacteria utilize soil organic matter and easily degrade plant residues as a source of the substrate to produce methane, and during the growth of rice plants by utilizing root exudates, root rot, and aquatic biomass (Dubey, 2005). Root exudation produces various compounds that are used as a substrate for microbial activity, including inorganic ions, amino acids, amides, sugars, aliphatic acids, aromatic acids, volatile aromatic compounds, gasses, ethylene, vitamins, peptides, proteins, enzymes, plant hormones, alcohol, a functional group of carbonyl, urea, phytoalexin (Dundek *et al.*, 2011).

The averaged CH_4 concentration has been increasing at the rate of 0.5-1% per year. The cumulative annual CH_4 emission is estimated at approximately 600 Tg CH_4 per year

(anthropogenic and natural sources), of which 20% was contributed by rice fields (Malyan *et al.*, 2016). Methane from paddy soil is released through plant media (more than 80%), diffusion, and ebullition (Jiang *et al.*, 2013). The amount of methane emitted from rice plants depends on variety, the morphological characteristics of plants including aerenchyma tissue, the availability of organic substrates, and the abundance of methanogenic and methanotrophic microbes (Neue, 1993; Dubey, 2005; Jugold *et al.*, 2012). Concentrations in soil solutions are relatively high in the reproductive growth phase of rice plants. Methane released in the reproductive plant growth phase is relatively higher than the ripening and vegetative phases. The difference in CH₄ emissions between varieties is determined by differences in production, oxidation, and methane transport capacity (Jiang *et al.*, 2013). Methane emissions in paddy fields are controlled by a complex set of biogeochemical characteristics from submerged soils and agricultural management practices. Several factors influence the pattern and magnitude of methane gas emissions, including soil type, water management, soil temperature, rice variety, organic matter, fertilization, and cropping seasons (Nazer *et al.*, 2018).

Indirectly, farmers have implemented efforts to mitigate methane gas emissions, for example by using superior varieties that have low methane emissions, providing organic material with a low C/N ratio, fertilizing N in the form of tablets or ZA, regulating irrigation water in rotation, applying without tillage, and provide ameliorant material (Wihardjaka and Setyanto, 2007; Naser *et al.*, 2018).

Nitrous oxide (N₂O) is produced as an intermediate result of the nitrification process and

the by-product of the denitrification process (Ruanpan and Mala, 2016; Ning *et al.*, 2018). In the early stages of the nitrification process, NH₄ is oxidized to NO₂ by ammonia-oxidizing bacteria and in the next stage, nitrite-oxidizing bacteria convert NO₂ to NO₃. The nitrate formed is reduced to N₂ and N₂O in the denitrification process where the N₂O gas contributes to the effects of global warming (Ruanpan and Mala, 2016). Nitrification and denitrification processes can occur in wet soil conditions where oxygen is limited and NO₃ is used as the main source of microbial denitrification. The agricultural sector contributes to anthropogenic N₂O emissions ranging from 70-80% (Torralbo *et al.*, 2017). The global agricultural system produces 30% NO and 70% N₂O released into the atmosphere where the global warming potential of N₂O is 298-300 times the CO₂ molecule (Reyes-Escobar *et al.*, 2015; Kang *et al.*, 2021). Soil N₂O flux depends on the application of N fertilizer, edaphoclimatic effect on microbial activity, temperature, O₂, pH, soil moisture, and the availability of organic C and total N in the soil (Torralbo *et al.*, 2017; Kang *et al.*, 2021). The increase in nitrogen (N) fertilizer application in agricultural ecosystems has been recognized as a major source of N₂O, representing approximately 60% of the global anthropogenic emission rates in 2005 (Li *et al.*, 2015).

Practical cultivation that can reduce nitrous oxide emissions, including returning plant residues in the form of compost, applying decomposed or containing nitrogen fertilizer slow-release, applying fertilizer gradually, applying direct seed planting, and applying urease inhibitors or nitrification inhibitors together with N fertilization and/or organic

fertilizer (Wihardjaka and Setyanto, 2007; Reyes-Escobar *et al.*, 2015). Paddy soil fertilized with urea with rice straw applied to emit nitrous oxide lower than without the application of rice straw (Mosier *et al.*, 2004).

NITRIFICATION INHIBITOR

Based on President Regulation 61/2011, the agricultural sector is targeted to reduce GHG emissions by 8 million tons of CO₂-e independently or 11 million tons of CO₂-e through international cooperation. The reduction in GHG emissions can be done with the action plan in President Regulation 61/2011, including the application of plant cultivation technology by utilizing bio-pesticides (IAARD, 2011). Most natural products for bio-pesticides also act as nitrification inhibitors. Nitrification inhibitors are defined as compounds or materials that specifically inhibit or retard the oxidation of ammonium to nitrite without affecting the subsequent oxidation of nitrite to nitrate (Sahrawat, 2004). Besides influencing nitrification in soil, nitrification inhibitors also affect physical, chemical, and biological processes affecting N transformations, other than nitrification, such as the transport,

movement, and persistence of N in the soil and its gaseous loss to the atmosphere (Sahrawat, 2004).

Some countries have used nitrification inhibitors formulations to reduce N losses and improve nitrogen fertilizer efficiency. The use of nitrogen fertilizers is generally inefficient were more than 70% of N fertilizer inputs can be lost or emitted into the atmosphere in the form of N₂ and N₂O or lost through nitrates leaching and ammonia volatilization (Reyes-Escobar *et al.*, 2015). The nitrification inhibitor can save the use of N fertilizer by 25% (Sahrawat, 2004). Inhibitors materials can retard the formation of nitrates and intermediate products of N₂O as presented in Figure 1. Nitrification inhibitors formulations that have been commercially available include nitrapyrin (2-chloro-6-(trichloromethyl) pyridine), 3,4-dimethyl pyrazole phosphate (DMPP), Dicyandiamide (DCD), and thiosulfates. These compounds suppress microbial activity for several days to weeks depending on soil moisture and soil type. The application of DCD and potassium thiosulfate (K₂S₂O₃) inhibit nitrification by 72.6% and 33.1%, respectively which cause delaying

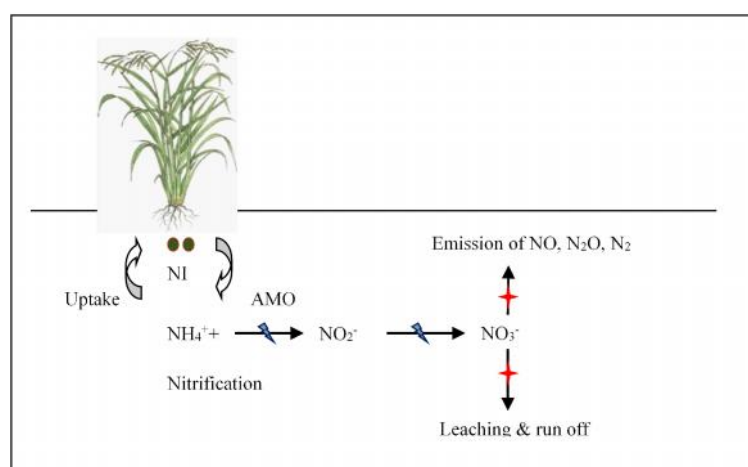


Figure 1 Scheme of nitrification inhibitor role in microbial nitrogen transformation (Source: Wang *et al.*, 2020)

nitrate formation during 30 and 10 days, respectively (Ning *et al.*, 2018). The use of DCD and DMPP reduced N_2O emissions by 25.8 and 48.7%, respectively (Benckiser *et al.*, 2015). The inhibition mechanism is not yet clear. Commercial nitrification inhibitors are generally expensive, so farmers are not interested in using them. In addition, commercial nitrification inhibitors are limited and show detrimental effects on the environment (Ruanpan and Mala, 2016).

The use of chemical agents (compounds or materials) that can inhibit or retard methane production and emission appear attractive for mitigating methane emission from rice fields (Sahrawat, 2004). The principle of inhibition is based on the toxic nature of the compound or element against methanogenic bacteria, such as secondary metabolites, halogenated methane, sulfites, sulfates, nitrates, Fe^{3+} , trichloroethyl pivalate, and long-chain unsaturated fatty compounds (Martin *et al.*, 2008). Several chemical compounds have been tested for use as inhibitors of methane formation, including ethylene, CH_3F , chloroform, organic compounds containing halogens, and pesticide compounds. Organic matter decomposition and methane production are inhibited in submerged soils that react acidly, nutrient supply is unbalanced, kaolinite clay content and oxidants are high (Neue, 1993). The application of CH_3F in the rice plant roots can oxidize the methane produced by 65% (Chan and Perkin, 2000). The research result of Jugold *et al.* (2012), the use of 2-bromoethanesulfonate (BES) and chloromethane (CH_3Cl) compounds effectively reduce methanogen microbial activity, which influences the methane production in the

plant rhizosphere. Martinez-Fernandez *et al.* (2016) tested methanogenesis inhibitors with bromochloromethane (BCM) and chloroform, and BCM could reduce 80% methane in green feed for dairy cows. Research results from Bharati *et al.* showed that nitrification inhibitors can inhibit methane production in alluvial soils following the order: thiourea < ammonium thiosulfate < aminopurine < pyridine < dicyandiamide (DCD) < sodium azide (Sahrawat, 2004). The mechanisms involved in mitigating methane production and emission by nitrification inhibitors are not fully understood (Sahrawat, 2004).

Higher plants contain diverse secondary metabolites with high structural diversity. Secondary metabolites in the form of phytochemical compounds can function as antibacterial or antifungal, including tannins, polyphenols, saponins, triterpenoids, alkaloids, and certain compounds in plants (Mazid *et al.*, 2011; Ku-Vera *et al.*, 2020; Cardoso-Gutierrez *et al.*, 2021). These compounds can reduce methanogenic activity and the ratio of acetate/propionate in the methanogenesis process (Patra *et al.*, 2006). Natural materials are abundantly available and have the potential to be used as nitrification inhibitors to conserve and improve nitrogen nutrients in the soil. The use of plant materials as nitrification inhibitors is easily degraded and has no negative impact on the environment. However, natural products such as nitrification inhibitors have not been widely used by farmers, and some farmers use them to control plant-disturbing organisms.

Many natural products from plants are used as nitrification inhibitors, as reported by Upadhyay *et al.* (2011) which covers *Brachiaria*

humidicola, *Pongamia glabra*, *Sorghum bicolor*, *Azadirachta indica*, *Camellia sinensis*, *Linum usitatissimum*, *Madhuca latifolia*, *Pyrethrum* spp., *Artemisia annua*, *Mentha spicata*, *Artemis afra*, *Echinops* spp, and *Eugenia caryophyllata*. The content of polyphenolic compounds such as lignin, tannin, melanin in agricultural waste is a natural nitrification inhibitor and antimicrobial (Maryana *et al.*, 2010). Some legume plants have the potential to be used as an inhibitor of the production of nitrous oxide and methane, as *Leucaena leucocephala*. *Leucaena leucocephala* is one of the most promising, which contains a wide variety of secondary compounds with potential methane-suppressing properties (Ku-Vera *et al.*, 2020). Several natural products can reduce the release of methane and nitrous oxide from paddy soils, including leaf of *Ageratum conyzoides*, leaf of *Cosmos caudatus*, turmeric rhizomes, and coffee waste (Table 1). The content of several secondary metabolites in these materials plays an important role in inhibiting the nitrification process and the formation of methane.

It can be seen from Table 2 that natural ingredients that can reduce GWP in Inceptisol

soils are the application of *Cosmos caudatus* biomass, coffee waste, turmeric rhizome, coconut fiber, and *Ageratum* leaves, respectively 11.8%; 12.5%; 23.7%; 55.3%; and 56.8%, while the natural nitrification inhibitors that were able to reduce the GWP value in vertisol soils were turmeric rhizome, *Cosmos caudatus* biomass, and coffee waste with a percentage of 27.8% respectively; 34.2%; and 37.7% (Susilowati *et al.*, 2021). The content of secondary metabolites in natural materials in the form of polyphenols or unsaturated fats can act as nitrification inhibitors by inhibiting the work of bacteria in the formation of CH_4 and maintaining nitrogen in the form of NH_4^+ (Susilowati *et al.*, 2021). The potential for CH_4 production from Inceptisols soil is higher than from Vertisols, on the other hand, the potential for N_2O production is higher in Vertisols than Inceptisols. Vertisols contain a high clay fraction which allows the negative charge on the surface to bind high NH_4^+ thereby inhibiting the formation of nitrate and nitrous oxide by-products (Susilowati *et al.*, 2021).

The research result of Wihardjaka *et al.* (2011, 2013) showed that the use of neem seeds (*Azadirachta indica*) is effective in reducing emissions of methane and nitrous oxide higher than carbofuran insecticide

Table 1 Potential of several natural products as nitrification inhibitors and methanogenesis in paddy soils

Natural materials	% CH_4 reduction	% N_2O reduction	GWP (mg $\text{CO}_2/\text{g soil}$) ¹⁾	% GWP reduction
Without nitrification inhibitor	-	-	20.17	-
Waste of tea leaves	-0.2	-33.5	24.48	-18.2
Coconut fiber	58.7	-67.5	22.66	-9.4
Coffea waste	15.5	11.5	17.94	13.4
Leaf of <i>Ageratum conyzoides</i>	58.4	3.2	14.79	28.6
Leaf of <i>Cosmos caudatus</i>	32.6	24.2	14.90	28.0
Turmeric rhizomes	34.4	61.9	10.51	49.3

Source: Annual Report of IAERI (2010)

¹⁾ GWP is computed using formula $\text{GWP}_{\text{CO}_2} = (21 \times \text{CH}_4) + (296 \times \text{N}_2\text{O})$

Table 2 Potential production of CH₄, N₂O, and global warming potential on Inceptisols and Vertisols applied some natural materials

Soil type	Natural materials	CH ₄ (mg CH ₄ /g soil)	N ₂ O (μg N ₂ O/g soil)	GWP (g CO ₂ -eq/g soil)
Inceptisols	No NI	0.74 ± 0.264	5.0 ± 1.35	0.018 ± 0.006
	Waste of tea leaves	0.81 ± 0.208	2.0 ± 0.86	0.019 ± 0.005
	Coconut fiber	0.33 ± 0.156	2.3 ± 0.91	0.008 ± 0.003
	Coffee wastes	0.68 ± 0.290	1.8 ± 0.84	0.016 ± 0.007
	Ageratum leaves	0.32 ± 0.128	1.8 ± 0.79	0.008 ± 0.003
	Cosmos biomass	0.64 ± 0.282	7.7 ± 10.52	0.016 ± 0.006
	Tumeric rhizome	0.52 ± 0.101	7.2 ± 1.97	0.014 ± 0.002
Vertisols	No NI	0.09 ± 0.013	70.5 ± 8.02	0.023 ± 0.004
	Waste of tea leaves	0.02 ± 0.011	131.2 ± 54.96	0.039 ± 0.016
	Coconut fiber	0.01 ± 0.004	113.6 ± 58.46	0.034 ± 0.017
	Coffee wastes	0.02 ± 0.004	42.5 ± 13.77	0.014 ± 0.004
	Ageratum leaves	0.02 ± 0.005	87.2 ± 37.27	0.026 ± 0.011
	Cosmos biomass	0.04 ± 0.013	48.4 ± 19.54	0.015 ± 0.006
	Tumeric rhizome	0.02 ± 0.012	54.2 ± 31.97	0.017 ± 0.009

Source: Susilowati *et al.* (2021)

NI = nitrification inhibitor, GWP = global warming potential, in-unit of equivalent CO₂ that computed from (21xCH₄)+(296xN₂O)

(Table 3). According to Sahrawat (2004) and Chen *et al.* (2008), neem seeds contain secondary metabolites as pesticide compounds which can function as nitrification inhibitors to inhibit the conversion of nitrates to nitrous oxide in the denitrification process. Neem powder applied together with nitrogen fertilization reduced N₂O emissions in direct-seeded and transplanted rice by 56.7 and 41.4%, respectively, compared to N fertilization alone (Table 4). In addition, the application of neem powder along with N fertilizer also increased the grain yield of rainfed rice by 1.2-5.4% and N uptake in the range of 2.2-4.0% compared to N fertilizer without neem powder (Wihardjaka, 2017). Natural nitrification inhibitors can be applied together with bio charcoal (biochar). Biochar

is charcoal prepared by pyrolytic processing (i.e., O₂-absent heating at 300-700°C) of residual biomass materials and used as a soil amendment in agricultural and environmental (Guo *et al.*, 2020). Biochar is multifunctional agent, namely improving soil fertility and soil productivity through increasing cations exchange capacity, water retention, aggregate stability, and soil porosity. Biochar also plays a role in soil bioremediation and mitigation of the effects of climate change (Martin *et al.*, 2015), as well as an ideal habitat for microbes (Reyes-Escobar *et al.*, 2015; Guo *et al.*, 2020). The biochar application decreases N₂O fluxes by 30.92%, as well as significantly affects soil CH₄ emission (Zhang *et al.*, 2020). Biochar amendment can enhance the populations of methanotrophic proteobacteria

Table 3 Use of nitrification inhibitors in mitigating CH₄ and N₂O emissions in rice fields in Central Java, Indonesia

Nitrification inhibitors	Methane emission (kg CH ₄ /ha/season) ¹⁾	Nitrous oxide emission (kg N ₂ O/ha/season) ¹⁾
Without nitrification inhibitor	87.9	0.33
Neem seeds	71.2	0.17
Carbofuran	82.0	0.26

¹⁾ Averaged values, Source: Wihardjaka *et al.* (2012, 2013)

Table 4 Use of neem powder together with N fertilizer on N₂O emission, grain yield, and N uptake in rainfed rice fields, Central Java, Indonesia

Fertilization	Nitrous oxide emission (g N ₂ O/ha/season)		Dry grain yield (t/ha)		N uptake (kg N/ha)	
	DSR	TPR	DSR	TPR	DSR	TPR
Urea	485±14	321±20	6.78±0.57	3.73±0.37	97.9±11.8	82.5±7.7
Urea+neem powder	210±12	188±36	6.86±0.18	3.93±0.38	101.9±10.8	84.3±4.0

Rice variety = Memberamo, Urea rate of 120 kg N/ha, neem powder rate of 15 kg/ha, Urea+neem powder is applied in three splits: 1/3 before planting, 1/3 at active tillering, and 1/3 at panicle initiation, DSR = direct-seeded rice in the wet season, TPR = transplanted rice in the dry season

Source: Wihardjaka (2017)

that oxidize methane production in soil and can reduce the populations of methanogenic archaea and methanotrophic archaea, which minimize the CH₄ emission from soil (Haider *et al.*, 2022).

CONCLUSION

Natural materials such as part of plants and agricultural wastes are abundantly available in the surrounding environment, inexpensive, and safe that can play an important role in mitigating the climate change impacts through the reduction of greenhouse gas emissions in rice fields. Natural materials from plants and agricultural wastes contain phytochemical compounds/secondary metabolites that function as anti-microbial, including inhibitors of microbiological processes in agricultural soils that inhibit nitrification and methanogenesis. Some natural ingredients are reported to be able to suppress methane formation more than 30%, namely coconut fiber, turmeric rhizomes, leaf of *Ageratum conyzoides*, and a leaf of *Cosmos caudatus*; and some of these substances also reduce the production of nitrous oxide more than 20%, namely, *Cosmos caudatus* and *Ageratum conyzoides*. The use of natural ingredients such as neem can reduce GHG emissions, increase grain yields, and N uptake of rice plants.

ACKNOWLEDGEMENTS

The authors thank our colleagues in the Institute for supporting some references and secondary data. We are also grateful to the anonymous reviewers who helped us to improve the quality of the manuscript.

REFERENCES

- Bappenas. 2019. *National Adaptation Plan: Executive Summary 2019*. Ministry of National Development Planning/ National Development Planning Agency (Bappenas). Jakarta. 28p.
- Benckiser G., Schartel T., Weishe A. 2015. *Control of NO₃⁻ and N₂O Emissions in Agroecosystems: A Review*. Agron. Sustain. Dev. 35: 1059-1074.
- Brodt S., Kendall a., Mohammadi Y., Arslan A., Yuan J., Lee I.S., Linquist B. 2014. *Life Cycle Greenhouse Gas Emissions in California Rice Production*. Field Crops Research. 169: 89–98. Doi: 10.1016/j.fcr.2014.09.007
- Cardoso-Gutierrez E., Aranda-Aguirre E., Robles-Jimenez L.E., Castelan-Ortega O.A., Chay-Canul A.J., Foggi G., Angeles-Hernandez J.C., Vargas-Bello-Perez E., Gonzalez-Ronquillo M. 2021. *Effect of Tannins from Tropical Plants on Methane Production from Ruminants: A Systematic Review*. Veterinary and Animal Science. 14: 100214. Doi: 10.1016/j.vas.2021.100214

- Chan A.S.K., Parkin T.B. 2000. *Evaluation of Potential Inhibitors of Methanogenesis and Methane Oxidation in A Landfill Cover Soil*. Soil Biology & Biochemistry. 32: 1581-1590.
- Chen D., Li Y., Grace P., Mosier, R.A. 2008. *N₂O Emissions from Agricultural Lands: A Synthesis of Simulation Approaches*. Plant & Soil. 309: 169-189.
- Du Y., Guo X., Li J., Liu Y., Luo J., Liang Y., Li T. 2022. *Elevated Carbon Dioxide Stimulates Nitrous Oxide Emission in Agricultural Soils: A Global Meta-Analysis*. Pedosphere. 32(1): 3–14. Doi: 10.1016/S1002-0160(21)60057-7
- Dubey S.K. 2005. *Microbial Ecology of Methane Emission in Rice Agroecosystem: A Review*. Applied Ecology & Environmental Research. 3(2): 1-27.
- Dundek P., Holík L., Rohlik T., Hromadko L., Vranova V., Rejsek K., Formanek P. 2011. *Methods of Plant Root Exudates Analysis: A Review*. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis. 32(3): 241-246.
- Gorh D., Baruah K.K., Gogoi N. 2018. *Analysis of Greenhouse Gas (Methane and Nitrous Oxide) Emission and Global Warming Potential from Rice Fields: with Reference to Biological Mitigation of Climate Change*. SDRP Journal of Earth Sciences & Environmental Studies. 3(2). Doi: 10.25177/JES.3.2.3
- Guo M., Song W., Tian J. 2020. *Biochar-Facilitated Soil Remediation: Mechanisms and Efficacy Variations*. Front. Environ. Sci. 8:521512. Doi: 10.3389/fenvs.2020.521512
- Haider F.U., Coulter J.A., Cai L., Hussain S., Cheema S.A., Wu J., Zhang R. 2022. *An Overview on Biochar Production, Its Implications, and Mechanisms of Biochar-Induced Amelioration of Soil and Plant Characteristics*. Pedosphere. 32(1): 107–130. Doi: 10.1016/S1002-0160(20)60094-7
- Haque M.M., Biswas J.C., Kim S.Y., Kim P.J. 2017. *Intermittent drainage in paddy soil: ecosystem carbon budget and global warming potential*. Paddy Water Environ. 15:403–411. Doi: 10.1007/s10333-016-0558-7
- Hussain S., Peng S., Fahad S., Khaliq A., Huang J., Cui K., Nie L. 2014. *Rice Management Interventions to Mitigate Greenhouse Gas Emissions: A Review*. Environ. Sci. Pollut. Res. Doi: 10.1007/s11356-014-3760-4
- IAARD. 2011. *General Guidelines of Climate Change Mitigation in Agricultural Sector*. Indonesian Agency for Agricultural Research and Development.
- IAERI. 2011. *Annual Report of IAERI Researchs Activity of 2010*. Indonesian Agricultural Environment Research Institute.
- Jiang Y., Wang L., Yan X., Tian Y., Deng A., Zhang W. 2013. *Super Rice Cropping will Enhance Rice Yield and Reduce CH₄ Emission: A Case Study in Nanjing, China*. Rice Science. 20(6): 427-433.
- Jugold A., Althoff F., Hurkuck M., Greule M., Lenhart K., Lelieveld J., Keppler F. 2012. *Non-Microbial Methane Formation in Oxic Soils*. Biogeosciences. 9: 5291–5301.

- Kang S.W., Yun J.J., Park J.H., Cheong Y.H., Park J.H., Seo D.C., Cho J.S. 2021. *Effects of Biochar and Barley Straw Application on The Rice Productivity and Greenhouse Gas Emissions of Paddy Field* Applied Biological Chemistry. 64: 92. Doi: 10.1186/s13765-021-00666-7
- KLHK. 2016. *First Nationally Determined Contribution Republic of Indonesia*. Kementerian Lingkungan Hidup dan Kehutanan.
- KLHK. 2019. *Peta Jalan Implementasi Nationally Determined Contribution: Mitigasi*. Direktorat Jenderal Pengendalian Perubahan Iklim Kementerian Lingkungan Hidup dan Kehutanan. Jakarta.
- Khudori. 2011. *Sistem Pertanian Pangan Adaptif Perubahan Iklim*. Pangan. 20(2): 105-119.
- Ku-Vera J.C., Jiménez-Ocampo R., Valencia-Salazar S.S., Montoya-Flores M.D., Molina-Botero I.C., Arango J., Gómez-Bravo C.A., Aguilar-Pérez C.F., Solorio-Sánchez F.J. 2020. *Role of Secondary Plant Metabolites on Enteric Methane Mitigation in Ruminants*. Front. Vet. Sci. 7:584. Doi: 10.3389/fvets.2020.00584
- Lagomarsino A., Agnelli A.E., Linquist B., Adviento-Borbe M.A., Agnelli A., Gavina G., Ravaglia S., Ferrara R.M. 2016. *Alternate Wetting and Drying of Rice Reduced CH₄ Emissions but Triggered N₂O Peaks in A Clayey Soil of Central Italy*. Pedosphere. 26: 533–548.
- Li B., Fan C.H., Xiong Z.Q., Li Q.L., Zhang M. 2015. *The Combined Effects of Nitrification Inhibitor and Biochar Incorporation on Yield-Scaled N₂O Emissions from An Intensively Managed Vegetable Field in Southeastern China*. Biogeosciences. 12: 2003–2017. Doi: 10.5194/bg-12-2003-2015
- Malyan S.K., Bhatia A., Kumar A., Gupta D.K., Singh R., Kumar S.S., Tomer R., Kumar O., Jain N. 2016. *Methane Production, Oxidation and Mitigation: A Mechanistic Understanding and Comprehensive Evaluation of Influencing Factor*. Science of the Total Environment. 572: 874–896. Doi: 10.1016/j.scitotenv.2016.07.182
- Martin C., Rouel J., Jouany J.P., Doreau M., Chilliard Y. 2008. *Methane Output and Diet Digestibility in Response to Feeding Dairy Cows Crude Linseed, Extruded Linseed, or Linseed Oil*. J. Anim. Sci. 86(10): 2642-2650. Doi: 10.2527/Jas.2007-0774
- Martin S.L., Clarke M.L., Othman M., Ramsden S.J., West H.M. 2015. *Biochar-Mediated Reductions in Greenhouse Gas Emissions from Soil Amended with anaerobic Digestates*. Biomass and Bioenergy. 79: 39-49. Doi: 10.1016/j.biombioe.2015.04.030
- Martinez-Fernandez G., Denman S.E., Yang C., Cheung J., Mitsumori M., McSweeney C.S. 2016. *Methane Inhibition Alters The Microbial Community, Hydrogen Flow, and Fermentation Response in The Rumen of Cattle*. Front. Microbiol. 7:1122. Doi: 10.3389/fmicb.2016.01122
- Maryana, Jatmiko S.Y., Pramono J. 2010. *Potential of Natural Materials Exploiting as nitrate Inhibitor to Realize Sustainable Agriculture in The Effort Independent of Foods*. Proceeding of National Seminar in Food and Energy Securities. Veteran National Development University,

- Yogyakarta. ISBN: 978-602-98216-0-4. Page 33-40. (in Indonesian)
- Mazid M., Khan T.A., Mohammad F. 2011. *Role of Secondary Metabolites in defense Mechanisms of Plants*. Biology & Medicine Special Issue. 3(2): 232-249.
- MEF. 2018. *Laporan Inventarisasi Gas Rumah Kaca dan MRV Nasional 2017 [Greenhouse Gas Inventory Report and National MRV 2017]*, http://ditjenppi.menlhk.go.id/reddplus/images/adminppi/dokumen/lap_igrk_2018.pdf (accessed on 07 November 2018).
- Mosier A., Wassmann R., Verchot L., King J., Palm C. 2004. *Methane and Nitrous Oxide Fluxes in Tropical Agricultural Soils: Sources, Sinks and Mechanisms*. Environment, Development and Sustainability. 6: 11–49.
- Naser H.M., Nagata O., Sultana S., Hatano R. 2018. *Impact of Management Practices on Methane Emissions from Paddy Grown on Mineral Soil over Peat in Central Hokkaido, Japan*. Atmosphere. 9: 212. Doi:10.3390/atmos9060212
- Ning J., Ai S., Cui L. 2018. *Dicyandiamide has More Inhibitory Activities on Nitrification than Thiosulfate*. PLoS ONE. 13(8): e0200598. Doi: 10.1371/Journal.Pone.0200598
- Nueu H.U. 1993. *Methane Emission from Rice Fields: Wetland Rice Fields may Make A Major Contribution to Global Warming*. BioScience. 43(7): 466-473.
- Patra A.K., Kamra D.N., Agarwal N. 2006. *Effect of Plant Extracts on In Vitro Methanogenesis, Enzyme Activities and Fermentation of Feed-in Rumen Liquor of Buffalo*. Animal Feed Science and Technology. 128(3-4): 276-291. Doi: 10.1016/j.anifeedsci.2005.11.001
- Piva J.T., Sartor L.R., Sandini I.E., Moraes A., Dieckow J., Bayer C., Rosa C.M. 2019. *Emissions of Nitrous Oxide and Methane in A Subtropical Ferralsol Subjected to Nitrogen Fertilization and Sheep Grazing in Integrated Crop-Livestock System*. Rev. Bras Cienc. Solo. 43:e0180140. Doi: 10.1590/18069657rbcs20180140
- Reyes-Escobar J., Zagal E., Sandoval M., Navia R., Munoz C. 2015. *Development of A Biochar-Plant-Extract-Based Nitrification Inhibitor and Its Application in Field Conditions*. Sustainability. 7: 13585-13596. Doi:10.3390/su71013585
- Ruanpan W., Mala T. 2016. *The Effect of Some Thai Medicinal Herb Extracts on nitrification Inhibition*. Modern Applied Science. 10(2): 146-158.
- Sahrawat K.L. 2004. *Nitrification Inhibitors for Controlling Methane Emission from Submerged Rice Soils*. Current Science. 87(8): 1084-1087.
- Santoso A.B. 2016. *The Impact of Climate Change on Food Crops Production in The Province of Maluku*. Penelitian Pertanian Tanaman Pangan. 35(1): 29-38.
- Susilawati H.L., Wihardjaka A., Nurhasan, Setyanto P. 2021. *The potency of Natural Materials for Reducing CH₄ and N₂O Productions from Paddy Soils*. Jurnal Ilmu Pertanian Indonesia. 26(4): 499-510. Doi: 10.18343/jipi.26.4.499
- Torralbo F., Menendez S., Barrena I., Estavillo J.M., Marino D., Gonzalez-Murua C. 2017. *Dimethyl Pyrazol-*

- Based Nitrification Inhibitors Effect on Nitrifying and Denitrifying Bacteria to Mitigate N₂O Emission*. Scientific Reports. 7: 13810. Doi:10.1038/s41598-017-14225-y
- Upadhyay R.K., Patra D.D., Tewari S.K. 2011. *Natural Nitrification Inhibitors for Higher Nitrogen Use Efficiency, Crop Yield, and for Curtailing Global Warming*. J. Trop. Agric. 49(1-2): 19-24.
- Wang L., Bowatte S., Hou F.J. 2020. *Research Progress of Biological Nitrification Inhibitor (BNI) in Reducing Nitrogen Loss and Improving Nitrogen Use Efficiency in Agricultural Production Systems*. Pratacultural Science. 37(3): 1-10. Doi: 10.11829/j.issn.1001-0629.2019-0190.
- Wihardjaka A. 2017. *Biji Mimba Turunkan Emisi Dinitrogen Oksida di Tanah Sawah Tadah Hujan*. Warta Penelitian dan Pengembangan Pertanian. 39(3): 5-7.
- Wihardjaka A., Setyanto P. 2007. *Emisi dan Mitigasi Gas Rumah Kaca dari lahan Sawah Irigasi dan Tadah Hujan*. pp. 55-87. Dalam: Fagi, A.M., Pasandaran E., Kurnia U. (eds.). *Pengelolaan Lingkungan Pertanian Menuju Mekanisme Pembangunan Bersih*. Badan Penelitian dan Pengembangan Pertanian.
- Wihardjaka A., Tandjung S.D., Sunarminto B.H., Sugiharto E. 2012. *Methane Emission from Direct Seeded Rice under The Influences of Rice Straw and Nitrification Inhibitor*. Indonesian Journal of Agricultural Science. 13(1): 1-11.
- Wihardjaka A., Tandjung S.D., Sunarminto B.H., Sugiharto E. 2013. *Nitrous Oxide Emission and Nitrogen Uptake Affected by Soil Amendment and Nematicide in Rainfed Rice Soils at Central Java*. Indonesian Journal of Agricultural Science. 14(2): 45-54.
- Zhang Q., Xiao J., Xue J., Zhang L. 2020. *Quantifying The Effects of Biochar Application on Greenhouse Gas Emissions from Agricultural Soils: A Global Meta-Analysis*. Sustainability. 12, 3436. Doi:10.3390/su12083436
