Evaluating the Impact of Single Application and Co-applications of Mangrove Biochar on CH$_4$ and N$_2$O Emissions, Soil Properties and Yield on Farmer’s Traditional Rice Cultivation

Patikorn Sriphirom
The Joint Graduate School of Energy and Environment (JGSEE) and Center of Excellence on Energy Technology and Environment, King Mongkut’s University of Technology Thonburi (KMUTT), Bangkok, Thailand
Email: poramanoo@gmail.com

Sirintornthep Towprayoon and Amnat Chidthaisong
The Joint Graduate School of Energy and Environment (JGSEE), Earth System Science Research Cluster and Center of Excellence on Energy Technology and Environment, King Mongkut’s University of Technology Thonburi (KMUTT), Bangkok, Thailand
Email: {sirin, amnat_c}@jgsee.kmutt.ac.th

Abstract—Application of biochar to replace traditional practice is limited due to its variation impact on rice yield and environmental outputs such as soil properties and Greenhouse Gas (GHG) emissions. This study cultivated rice in the wet and dry seasons to compare effect of single application (BI) and co-applications of mangrove biochar with compost (BC) or chemical fertilizer (BF) with farmer’s traditional practice (CT) in order to recommend the optimum practice for yield increasing and GHG reduction. As compared to CT, it showed that BI, BC and BF reduced the seasonal emissions of CH$_4$ by 39.4%, 29.3% and 10.9% and N$_2$O by 32.9%, 31.2% and 9.42%, respectively. Soil pH, OM, C and CEC were increased while bulk density was reduced for all of BI, BC and BF significantly. After two cultivation seasons, SOC stock significantly increased by 45.3%, 45.9% and 45.0% in BI, BC and BF respectively. BI and BC significantly reduced grain yield by 21.4% and 11.8% respectively but was enhanced in BF by 3.94%. Therefore, co-application of biochar with chemical fertilizer is the optimal practice to promote the replacement of farmer’s traditional practice in order to improve soil properties and increase yield with partially mitigated CH$_4$ and N$_2$O emissions.

Index Terms—biochar application, biochar co-application, CH$_4$ emission, N$_2$O emission, SOC stock, rice yield

I. INTRODUCTION

Thailand is an agricultural country with rice growing area covered 46.9% of total agricultural area, accounted for 21.8% of total area in the country [1]. Rice cultivation of Thai farmers were mostly conducted according to traditional practice that apply chemical fertilizer with continuously flooded water management. It contributed the emissions at 27.9 Tg CO$_2$ eq., accounted for more than half of total emissions in agricultural sector [2]. This continuous traditional practice also results to the reduction of soil fertility and yield production in the long term.

Biochar is a recommended technology for GHG emissions mitigation with soil fertility improvement and yield enhancement. With carbon rich material that derived from of the biomass pyrolysis, biochar was reported on the mitigation potential of CH$_4$ and N$_2$O emissions from rice cultivation [3]. The field experiment in China showed the reduction of N$_2$O emission of biochar amendment by 21.1–27.6% as compared to no amendment soil [4]. While the rice paddy in Korea reported the CH$_4$ emission decrease by 33.8–35.7% as result of biochar addition as compared to without biochar treatment [5]. Reduction of both gases might be related to the aeration improvement of soil amended with biochar. This improvement would lead to the changes in the functionality and diversity of denitrifiers that affect the activity inhibiting of denitrifiers in soils as result to N$_2$O emission decrease [4], [6]. Meanwhile, this condition promotes the CH$_4$ oxidation bacteria and increase CH$_4$ oxidation rate [7]. Biochar also improve soil health such as pH adjustment particularly acidic soil [8] and Cation Exchange Capacity (CEC) enhancement [9]. It increase s absorption capacity of soil for nutrients [10] and water [11] and increase fertilizer use efficiency [12] due to its high porosity and surface area properties [13]. In term of rice yield, report of yield enhancement as compared to soil without amendment was found [14]. However, although these results were studied in other countries, but few have been found in Thailand, despite Thailand is large rice production area. In addition, it has not been studied in sandy loam soil (Khao Yoi (Kyo) soil series) which is one important type of rice cultivation soil in Thailand [15].
Although, biochar was reported these above benefits, but there are also studies that report the opposite results. Ref. [4] showed the increase of CH₄ emissions while Ref. [16] demonstrated the increase of N₂O emissions and the decrease of rice yield particularly when compared with fertilizer application. These results may be the major barrier that biochar is still not being used for farmers application particularly yield reduction. Therefore, this study aims to evaluate the effect of the single application and co-applications of biochar with fertilizers to recommend the optimal practice of rice cultivation with lower GHG emissions, improved soil properties and higher yield in order to replace the farmer’s traditional practice.

II. MATERIALS AND METHODS

A. Experimental Site

The study was conducted in the experimental paddy field (13° 35' 10" N & 99° 30' 21" E, 118 m above mean sea level), located in the Chombueng district, Ratchaburi province, western region of Thailand (Fig. 1). The soil was classified as Khao Yoi (Kyo) soil series with a sandy loam texture. The average of precipitation and air temperature during the experimental period was 2.80 mm day⁻¹ and 28.1 °C respectively. This site was changed from abandoned field (more than 10 years) to be the pre-crop for soil improving prior the experiment. Experimental field for this study. Rice was cultivated from abandoned field (more than 10 years) to be the pre-crop for soil improving prior the experiment. Rice was cultivated followed traditional practice during Feb. to Jun. 2015 to be the pre-crop for soil improving prior the experiment. The physical and chemical soil properties at depth of 0-20 cm were showed in Table I.

![Figure 1. Map showing the location of the experimental field in Ratchaburi Province, Thailand.](image)

**TABLE I. BASIC PHYSICAL AND CHEMICAL PROPERTIES OF SOIL, BIOCHAR AND COMPOST**

| Parameters | Soil | Biochar | Compost |
|------------|------|---------|---------|
| pH         | 6.12 | 7.94    | 7.12    |
| OM         | 0.86% | 11.19%  | 51.45%  |
| C          | 0.31% | 65.94%  | 19.10%  |
| N          | 0.08% | 0.24%   | 0.85%   |
| P          | 52.91 mg kg⁻¹ | 0.23% | - |
| K          | 85.39 mg kg⁻¹ | 0.10% | - |
| CEC        | 4.94 cmol kg⁻¹ | 13.87% | - |
| BD         | 1.64 g cm⁻³ | -     | -      |

B. Experimental Design and Crop Management

This experiment consist of four treatments were traditional practice (control: CT), single application of biochar (BI), co-application of biochar with compost (BC) and co-application of biochar with chemical fertilizer (BF). The seedlings of Pathumthani rice (*Oryza sativa L.*) cultivar were planted in the trays for 2 weeks and moved to transplanting with initial 4 tillers in a field under continuous flooding water management. Rice was cultivated for 2 seasons were wet season in Aug. to Dec. of 2015 and dry season in Feb. to Jun. of 2016. The crop residue was incorporated into the soil before rice transplanting for 30 days. While mangrove (*Rhizophora apiculata*) biochar (size of 1–2 mm) and Bangkok compost (see the properties in Table I) were incorporated before 15 days of transplanting at rate of 10 t ha⁻¹ year⁻¹ (assuming that two seasons per year) and 1.5 t ha⁻¹ season⁻¹, respectively. Chemical fertilizer at rate of 90 kg N ha⁻¹ season⁻¹ was applied two times during rice production season followed traditional practice. Compound fertilizer (N-P₂O₅-K₂O: 15-15-15) was applied as basal fertilizer at 20 days after transplanting (DAT) (33 kg N ha⁻¹) while urea was applied as top dressing at 60 DAT (57 kg N ha⁻¹). The crop duration of all treatments was ranging from 110 – 118 days. The experiment was carried out in a randomized complete block design by each plot size was 20 m².

C. CH₄ and N₂O Emissions Measurement

The closed chamber technique was used to measured CH₄ and N₂O emissions from the experimental field since transplanting to harvesting at three points in each plot [17]. The chamber made from acrylic opaque which has a size of 30 (width) x 30 (length) x 30 cm. The air sample in the headspace of chamber was sampled at 0, 5, 10 and 15 minutes after chamber closure once a week during 10.00 a.m. to 2.00 p.m. The samples were analyzed the concentrations of CH₄ and N₂O by using a Gas Chromatograph (GC). CH₄ used GC equipped with a Flame Ionization Detector (FID) and a Unibead C Packed column (Shimadzu GC-2014, Japan), using helium as a carrier gas. N₂O used GC equipped with Electron Capture Detector (ECD) and Porapak column (Shimadzu GC-14B, Japan). The seasonal cumulative CH₄ and N₂O emissions were calculated by the successive linear interpolation and numerical integration between the sampling days, assumed that both emissions followed a linear trend on the days when gases were not measured [18]. The GWP of the two gases were calculated as the mass of CO₂-eq over 100-year time horizon multiplied by 28 for CH₄ and 265 for N₂O [19].

D. Soil Sampling and Analysis

Soil at depth of 0-20 cm was collected by undisturbed sampling with three points per plot. It was analyzed pH (H₂O) (pH, ISE, ORP meter HI5222, Hanna Instrument), Organic Matter (OM) and Carbon (C) (Walkley-Black method), Nitrogen (N) (Kjeldahl method), available Phosphorus (P) (Bray II method), and available potassium (K) and CEC (ammonium acetate method) were analyzed following the methods descriptions in Ref.
Soil was dried by oven (Forced Air Convection Drying Oven, redline RF53, Germany) and calculated the Bulk Density (BD) and Soil Organic Carbon (SOC) stock by using the given equations by Ref. [21].

E. Plant Growth and Yield Measurement

The height of rice plant was manually measured by measuring tape from the soil surface to highest leaf. Grain yield and biomass was collected in the area of one square meter. It was dried by air and oven (Forced Air Convection Drying Oven, redline RF53, Germany) before weighing. The sampling was conducted with three points in each plot.

F. Statistical Analysis

The results were statistically analyzed using One Way Analysis of Variance (ANOVA) and Duncan’s multiple range tests of SPSS version 22 at 95% confidence level and standard errors are given as ± SE.

III. Results and Discussion

A. Seasonal Cumulative CH₄ and N₂O Emissions

The seasonal cumulative CH₄ and N₂O emissions in both cultivation seasons were reduced in all single application and co-applications of biochar. As compared to CT, the seasonal cumulative reduction of CH₄ was found in BI, BC and BF by 38.2%, 31.2% and 10.2% in wet season and 40.5%, 27.4% and 11.5% in dry season, respectively (Fig. 2a). While N₂O was reduced in BI, BC and BF by 31.6%, 30.9% and 7.00% in wet season and 34.2%, 31.4% and 11.8% in dry season, respectively (Fig. 2b). It resulted to GWP of all of single application and co-applications were reduced as well when compared with traditional practice (Fig. 2c). However, this effect showed the significant difference in BI and BC but no significant in BF under both seasons (Fig. 2).

The results showed that chemical fertilizer that applied in CT and BF caused high emissions of CH₄ and N₂O. Chemical fertilizer was reported the increase of CH₄ production [22], [23] and emission [24] as well as CH₄ oxidation suppression [25]. In addition, higher rice biomass of both treatments that incorporated into the soil might be another cause of higher CH₄ emission. The difference result between BF and CT, although no significance occurred but showed the mitigation potential of biochar. Ref. [4] demonstrated that the application of biochar in different rates affected different mitigation potentials. It was reported that the reduction of CH₄ emission in biochar amendments due to biochar increase oxidants (electron acceptors) [14] that might inhibit or slow down the CH₄ production under anaerobic soil particularly in the first period. Biochar addition into the soil improve soil aeration with bulk density reduction (see result in Table II) that promotes the oxidation rate of CH₄ [26]. Ref. [7] reported that the CH₄ emission reduction related to the increasing the growth of methanotrophic bacteria and the decrease of the abundance ratio of methanogenic archaea to methanotrophic bacterial. In term of N₂O emission reduction, biochar could increase soil pH which favor for the activity of N₂O reductase from denitrifying microorganisms [27], while suppression the activity of enzyme reductases related in the conversion of nitrite and nitrate to nitrous oxide [26]. While the higher CH₄ emissions that found in BC as compared to BI showed that compost increase organic matter availability in soil for methane generation by methanogens.
sequestration can occur for a long time [16]. This is in accordance to the studies which showed that biochar increased SOC stock by 8.49% to 25% [8]. It was also observed that compost and chemical fertilizer did not show the important impact on SOC stock. The reduction of bulk density was supported by the increase of soil aeration as result of high porosity and surface area of biochar material [11], [13]. In addition, this property of biochar also increases the adsorption capacity of soil nutrients [13]. It was consistent with the increase of soil CEC which showed the capacity in cations holding (most of them are nutrients) of soil [29].

C. Rice Growth and Yield

The results in Table III showed the significant reduction of rice yield in BI and BC by 21.9% and 12.3% in wet season and 20.9% and 11.3% in dry season as compared to CT, respectively. Both BI and BC are also significantly reduced aboveground biomass, although BC significantly obtained more rice yield and biomass than BI. On the other hand, BF was significantly increased rice yield and aboveground biomass as compared to CT except yield in wet season (see Table III). The higher 3.48 – 4.41% of rice yield and 8.40 – 14.5% of aboveground biomass in BF than CT showed the biochar potential for rice growth and yield development. The results showed the strong impact on yield and biomass production in fertilizers (compost and chemical fertilizer) over biochar alone and it was observed that chemical fertilizer has stronger effect than compost [30]. It was due to fertilizers particularly chemical fertilizer directly increased necessary nutrients for rice growth [31] as result to significant obtaining of more tiller, panicle and rice height led to the yield and biomass of CT and BF over BC and BI as well as BC more than BI (Table III). The promotion of higher rice growth and yield in BF due to biochar increases soil nutrients absorption capacity [10], [11] as well as increases nutrients use efficiency particularly nutrients from inorganic fertilizer [32]. However, the yield increase in this study is not much might be due to low biochar application rate as compared with the cases in previous studies [4], [33].

| Treatment | pH (H₂O) | OM | C | N | P | K | CEC | BD |
|-----------|----------|----|---|---|---|---|-----|----|
|           | %        | %  | % | % | mg kg⁻¹ | mg kg⁻¹ | cmol kg⁻¹ | g cm⁻³ |
| Wet season|          |    |   |   |     |     |      |     |
| CT        | 5.97 b   | 0.85 b | 0.34 b | 0.09 b | 14.5 b | 54.7 b | 4.96 b | 1.63 a |
| BI        | 6.33 a   | 1.20 a | 0.52 a | 0.07 b | 12.4 b | 40.8 c | 7.02 a | 1.54 b |
| BC        | 6.30 a   | 1.23 a | 0.53 a | 0.08 b | 12.6 b | 45.2 c | 6.86 a | 1.54 b |
| BF        | 6.20 a   | 1.24 a | 0.52 a | 0.11 a | 20.6 a | 75.2 a | 6.83 a | 1.55 b |
| Dry season|          |    |   |   |     |     |      |     |
| CT        | 5.92 C   | 0.87 B | 0.34 B | 0.10 A | 15.1 A | 46.2 B | 5.06 C | 1.67 A |
| BI        | 6.36 A   | 1.25 A | 0.52 A | 0.07 B | 12.2 B | 35.3 B | 7.22 A | 1.54 B |
| BC        | 6.33 A   | 1.28 A | 0.53 A | 0.09 A | 12.2 B | 37.6 B | 6.93 AB | 1.55 B |
| BF        | 6.15 B   | 1.26 A | 0.52 A | 0.12 A | 15.2 A | 68.3 A | 6.81 B | 1.57 B |

Figure 3. SOC stock after wet and dry cultivation seasons at 0-20 cm soil depth.

### TABLE II. PADDY SOIL PROPERTIES AT DEPTH OF 0-20 CM AFTER WET AND DRY CULTIVATION SEASONS

| Treatment | pH (H₂O) | OM | C | N | P | K | CEC | BD |
|-----------|----------|----|---|---|---|---|-----|----|
|           | %        | %  | % | % | mg kg⁻¹ | mg kg⁻¹ | cmol kg⁻¹ | g cm⁻³ |
| Wet season|          |    |   |   |     |     |      |     |
| CT        | 5.97 b   | 0.85 b | 0.34 b | 0.09 b | 14.5 b | 54.7 b | 4.96 b | 1.63 a |
| BI        | 6.33 a   | 1.20 a | 0.52 a | 0.07 b | 12.4 b | 40.8 c | 7.02 a | 1.54 b |
| BC        | 6.30 a   | 1.23 a | 0.53 a | 0.08 b | 12.6 b | 45.2 c | 6.86 a | 1.54 b |
| BF        | 6.20 a   | 1.24 a | 0.52 a | 0.11 a | 20.6 a | 75.2 a | 6.83 a | 1.55 b |
| Dry season|          |    |   |   |     |     |      |     |
| CT        | 5.92 C   | 0.87 B | 0.34 B | 0.10 A | 15.1 A | 46.2 B | 5.06 C | 1.67 A |
| BI        | 6.36 A   | 1.25 A | 0.52 A | 0.07 B | 12.2 B | 35.3 B | 7.22 A | 1.54 B |
| BC        | 6.33 A   | 1.28 A | 0.53 A | 0.09 A | 12.2 B | 37.6 B | 6.93 AB | 1.55 B |
| BF        | 6.15 B   | 1.26 A | 0.52 A | 0.12 A | 15.2 A | 68.3 A | 6.81 B | 1.57 B |

### TABLE III. THE AVERAGE OF THE GROWTH AND PRODUCTIVITIES OF RICE CULTIVATION IN WET AND DRY SEASONS

| Treatment | Tiller (tiller hill⁻¹) | Panicle (panicle hill⁻¹) | Rice height (cm) | Aboveground biomass (t ha⁻¹) | Grain yield (t ha⁻¹) |
|-----------|-----------------------|-------------------------|-----------------|-----------------------------|--------------------|
| Wet season|                       |                         |                 |                             |                    |
| CT        | 21.4 b                | 26.0 b                  | 90.7 b          | 11.0 b                      | 6.58 a             |
| BI        | 14.5 d                | 17.3 d                  | 70.5 d          | 6.01 d                      | 5.14 c             |
| BC        | 16.9 c                | 20.0 c                  | 76.0 c          | 7.77 c                      | 5.77 b             |
| BF        | 22.3 a                | 28.3 a                  | 96.5 a          | 12.6 a                      | 6.87 a             |
| Dry season|                       |                         |                 |                             |                    |
| CT        | 22.8 B                | 29.0 A                  | 94.9 B          | 11.9 B                      | 6.61 B             |
| BI        | 17.8 D                | 22.0 C                  | 74.8 D          | 8.13 D                      | 5.23 D             |
| BC        | 20.3 C                | 24.2 B                  | 79.7 C          | 8.75 C                      | 5.86 C             |
| BF        | 24.2 A                | 29.5 A                  | 99.7 A          | 12.9 A                      | 6.84 A             |
IV. CONCLUSIONS

The single application of biochar could highest mitigate CH₄ and N₂O emissions from rice cultivation with soil properties improving but its yield is unsatisfied as compared to traditional practice. When biochar was applied as co-applications with compost or chemical fertilizer, rice yield was found the increase only in the co-application with chemical fertilizer when compared with traditional practice. Soil properties under both co-applications were improved as well as CH₂ and N₂O emissions were reduced, although it was no significant decrease in co-application with chemical fertilizer as compared to traditional practice. Therefore, the optimal practice in replacing traditional practice that can be benefit to farmers is co-application of biochar with chemical fertilizer due to increasing of yield and improvement of soil properties with partial reduction of the GHG emissions. The further study should be designed to significantly enhance the potential of GHG mitigation and yield production of the recommended practice (biochar+chemical fertilizer) by may increase application rate of biochar or change the water management of rice cultivation.

ACKNOWLEDGMENT

This study was funded by the Joint Graduate School of Energy and Environment (JGSEE) and Center of Excellence of Energy Technology and Environment at King Mongkut’s University of Technology Thonburi (KMUTT) and the Thailand Research Fund (TRF) through the International Research Network Program (IRN) (IRN57W0001, IRN5701PHDW06). The study area was provided by Earth Systems Science King Mongkut’s University of Technology Thonburi.

CONFICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Patikorn Sripriom conducted the research, analyzed data and wrote the paper; Sirintornthep Towprayoon and Amanat Chidthaisong checked the data analysis; all authors had approved the final version of paper.

REFERENCES

[1] Agricultural Statistics of Thailand 2016 (in Thai), OAE (Office of Agricultural Economics), Ministry for Agriculture and Cooperatives, Bangkok, Thailand, 2016, ch. 11, pp. 170-182.
[2] Second Biennial Update Report of Thailand, ONEP (Office of Natural Resources and Environmental Policy and Planning), Ministry of Natural Resources and Environment, Bangkok, Thailand, 2017, ch. 2, pp. 27-30.
[3] Y. Liu, M. Yang, Y. Wu, H. Wang, Y. Chen, and W. Wu, “Reducing CH₄ and CO₂ emissions from waterlogged paddy soil with biochar,” J. Soil Sediment., vol. 11, pp. 930-939, 2011.
[4] A. Zhang, L. Cui, G. Pan, L. Li, Q. Hussain, X. Zhang, J. Zheng, and D. Crowley, “Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China,” Agric. Ecosyst. Environ., vol. 139, no. 4, pp. 469-475, 2010.
[5] J. Kim, G. Yoo, D. Kim, W. Ding, and H. Kang, “Combined application of biochar and slow-release fertilizer reduces methane emission but enhances rice yield by different mechanisms,” Appl. Soil Ecol., vol. 117, pp. 57-62, 2017.
[6] M. A. Cavigelli and G. P. Robertson, “Role of denitrifier diversity in rates of nitrous oxide consumption in a terrestrial ecosystem,” Soil Biol. Biochem., vol. 33, pp. 297-310, 2001.
[7] Y. Feng, Y. Xu, Y. Yu, Z. Xie, and X. Lin, “Mechanisms of biochar decreasing methane emission from Chinese paddy soils,” Soil Biol. Biochem., vol. 46, pp. 80-88, 2012.
[8] K. Y. Chan, L. V. Zvästen, I. Meszaros, A. Downie, and S. Joseph, “Agronomic values of greenwaste biochar as a soil amendment,” Soil Res., vol. 45, no. 8, pp. 629-634, 2007.
[9] G. Cornelissen, et al., “Biochar effect on maize yield and soil characteristics in five conservation farming sites in Zambia,” Agronomy, vol. 3, no. 2, pp. 256-274, 2013.
[10] S. Bhattacharjya, R. Chandra, N. Pareek, and K. P. Raverkar, “Biochar and crop residue application to soil: Effect on soil biochemical properties, nutrient availability and yield of rice (Oryza sativa L.) and wheat (Triticum aestivum L.),” Arch. Agron. Soil Sci., vol. 62, no. 8, pp. 1095-1108, 2015.
[11] Y. Chen, Y. Shinogi, and M. Taura, “Influence of biochar use on sugarcane growth, soil parameters, and groundwater quality,” Aust. J. Soil Res., vol. 48, pp. 526-530, 2010.
[12] C. Steiner, B. Glaser, W. G. Teixeira, J. Lehmann, W. E. Blum, and W. Zech, “Nitrogen retention and plant uptake on a highly weathered central Amazonian Ferralsol amended with compost and charcoal,” J. Plant Nutr. Soil Sci., vol. 171, no. 6, pp. 893-899, 2008.
[13] A. Downie, P. Munroe, and A. Crosky, “Physical properties of biochar,” in Biochar for Environmental Management: Science and Technology, J. Lehmann and S. Joseph, Eds., London, U.K.: Earthscan Press, 2009, ch. 2, pp. 13-29.
[14] D. Dong, Q. Feng, K. McGrouther, M. Yang, H. Wang, and W. Wu, “Effects of biochar amendment on rice growth and nitrogen retention in a waterlogged paddy field,” J. Soil Sci. Sediment., vol. 15, pp. 153-162, 2015.
[15] T. Attanandana, Paddy Soil Science (in Thai), 4th ed., Bangkok: Department of Soil Science, Faculty of Agriculture, Kasetsart University, 2007, ch. 5, pp. 63-83.
[16] Z. Xie, et al., “Impact of biochar application on nitrogen nutrition of rice, greenhouse-gas emissions and soil organic carbon dynamics in two paddy soils of China,” Plant and Soil, vol. 370, no. 1-2, pp. 527-540, 2013.
[17] K. Minamikawa, T. Tokida, S. Sudo, A. Padre, and K. Yagi, Guidelines for Measuring CH₄ and N₂O Emissions from Rice Paddies by a Manually Operated Closed Chamber Method, 1st ed., Tsukuba, Japan: NIAES, 2015, ch. 3-5, pp. 24-55.
[18] A. Chidthaisong, et al., “Evaluating the effects of Alternate Wetting and Drying (AWD) on methane and nitrous oxide emissions from a paddy field in Thailand,” Soil Sci. Plant Nutr., vol. 64, pp. 31-38, 2018.
[19] G. Myhre, et al., “Anthropogenic and natural radiative forcing,” in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, T. F. Stocker, et al., Eds., New York, USA: Cambridge University Press, 2013, ch. 8, pp. 659-740.
[20] L. P. V. Reeve, Procedures for Soil Analysis, 6th ed., Wageningen, the Netherlands: International Soil Reference and Information Centre, Food and Agriculture Organization of the United Nations, 2002, p. 199.
[21] M. Schrumpf, E. D. Schulze, K. Kaiser, and J. Schumacher, “How accurately can soil organic carbon stocks and stock changes be quantified by soil inventories?” Biogeosci. Discuss., vol. 8, no. 1, pp. 723-769, 2011.
[22] D. C. Parashar, J. Rai, K. G. Prabhate, and N. Singh, “Parameters affecting methane emission from paddy fields,” Indian J. Radio Space Phys., vol. 20, pp. 12-17, 1991.
[23] C. W. Lindau, “Methane emissions from Louisiana rice fields amended with nitrogen fertilizers,” Soil Biol. Biochem., vol. 26, pp. 353-359, 1994.
[24] D. Kong, et al., “Linking methane emissions to methanogenic and methanotrophic communities under different fertilization strategies in rice paddies,” Geoderma, vol. 347, pp. 233-243, 2019.
[25] S. K. Dubey, “Spatio-kinetic variation of methane oxidizing bacteria in paddy soil at mid-tillering: Effect of N-fertilizers,” *Nutr. Cycl. Agroecosys.*, vol. 65, pp. 53-59, 2003.

[26] V. L. V. Zwieten, B. Singh, S. Joseph, S. Kimber, A. Cowie, and Y. K. Chan, “Biochar and emissions of non-CO$_2$ greenhouse gases from soil,” in *Biochar for Environmental Management: Science and Technology*, J. Lehmann and S. Joseph, Eds., London, U.K.: Earthscan Press, 2009, ch. 13, pp. 227-249.

[27] Y. Yanai, K. Toyota, and M. Okazaki, “Effect of charcoal addition on N$_2$O emissions from soil resulting from rewetting air-dried soil in short-term laboratory experiments,” *Soil Sci. Plant Nutr.*, vol. 53, pp. 181-188, 2007.

[28] J. H. Yuan, R. K. Xu, and H. Zhang, “The forms of alkalis in the biochar produced from crop residues at different temperatures,” *Bioresour. Technol.*, vol. 102, no. 3, pp. 3488-3497, 2011.

[29] E. W. Bruun, “Application of fast pyrolysis biochar to a loamy soil - Effects on carbon and nitrogen and potential for carbon sequestration,” Ph.D. dissertation, The National Laboratory of Sustainable Energy, Technical University of Denmark, Kgs. Lyngby, 2011.

[30] S. T. Partey, R. F. Preziosi, and G. D Robson, “Short-term interactive effects of biochar, green manure, and inorganic fertilizer on soil properties and agronomic characteristics of maize,” *Agric. Res.*, vol. 3, no. 2, pp. 128-136, 2014.

[31] M. A. R. Sarker, M. Y. A. Pramanik, G. M. Faruk, and M. Y. Ali, “Effect of green manures and levels of nitrogen on some growth attributes of transplant aman rice,” *Pak. J. Biol. Sci.*, vol. 7, pp. 739-742, 2004.

[32] P. Blackwell, E. Krull, G. Butler, A. Herbert, and Z. Soloiman, “Effect of banded biochar on dryland wheat production and fertiliser use in south-western Australia: An agronomic and economic perspective,” *Soil Res.*, vol. 48, no. 7, pp. 531-545, 2010.

[33] S. Koyama, T. Katagiri, K. Minamikawa, M. Kato, and H. Hayashi, “Effects of rice husk charcoal application on rice yield, methane emission, and soil carbon sequestration in andosol paddy soil,” *JARQ-JPN Agr. Res. Q.*, vol. 50, no. 4, pp. 319-327, 2016.

---

**Patikorn Sriphirom** was born in Bangkok on May 16, 1992. He graduated Bachelor of Science (public health) in 2014 from Thammasat University, Phathumthani, Thailand and Master of Science in environmental technology in 2017 from the Joint Graduate School of Energy and Environment (JGSEE) at King Mongkut’s University of Technology Thonburi (KMUTT), Bangkok, Thailand. Currently, he is a Ph.D. student in environmental technology at the same place with Master level. His master and Ph.D. thesis focus on GHG emissions mitigation from rice cultivation with new technologies to adoption of farmers. He is also a research assistant of Technology development for circulatory food production systems responsive to climate change (Development of mitigation option for greenhouse gases emissions from agricultural lands in Asia) Project (Funded by National Institute for Agro-Environmental Sciences, National Agriculture and Food Research Organization) and healthy soil management for combating climate change in Southeast Asia project (Funded by Food and Agriculture Organization of the United Nations). His recent publication entitled “Effect of alternate wetting and drying water management on rice cultivation with low emissions and low water used during wet and dry season,” *Journal of Cleaner Production*, vol. 223, pp. 980-988.