Evaluating the Impact of Single Application and Co-applications of Mangrove Biochar on CH_4 and N_2O Emissions, Soil Properties and Yield on Farmer's Traditional Rice Cultivation

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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_2O 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_2O emissions.

Index Terms—biochar application, biochar co-application, CH_4 emission, N_2O 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_2O emissions from rice cultivation [3]. The field experiment in China showed the reduction of N_2O 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_2O 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 increases 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 CH_4 emissions while Ref. [16] demonstrated the increase of N_2O 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. METERIALS 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 ^{o}C respectively. This site was changed from abandoned field (more than 10 years) to be the experimental field for this study. 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.
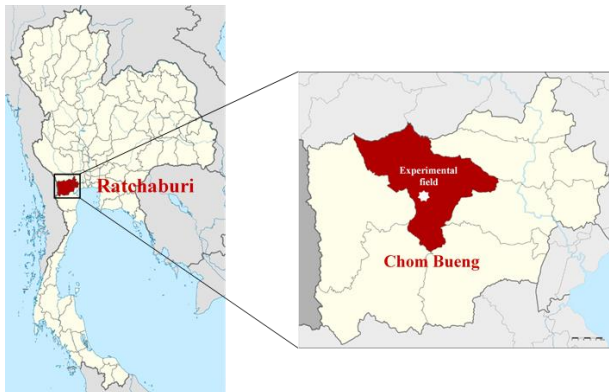

Figure 1. Map showing the location of the experimental field in Ratchaburi Province, Thailand.

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 1 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-P$_2$O$_5$-K$_2$O: 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 m^2.

C. CH_4 and N_2O Emissions Measurement

The closed chamber technique was used to measured CH_4 and N_2O 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, 60 or 120 (height) 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 CH_4 and N_2O by using a Gas Chromatograph (GC). CH_4 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. N_2O used GC equipped with Electron Capture Detector (ECD) and Porapak column (Shimadzu GC-14B, Japan). The seasonal cumulative CH_4 and N_2O 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 CO_2-eq over 100-year time horizon multiplied by 28 for CH_4 and 265 for N_2O [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.

[20]. 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 $\pm SE$.

III. RESULTS AND DISCUSSION

A. Seasonal Cumulative CH_4 and N_2O Emissions

The seasonal cumulative CH_4 and N_2O 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 CH_4 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 N_2O 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 CH_4 and N_2O. Chemical fertilizer was reported the increase of CH_4 production [22], [23] and emission [24] as well as CH_4 oxidation suppression [25]. In addition, higher rice biomass of both treatments that incorporated into the soil might be another cause of higher CH_4 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 CH_4 emission in biochar amendments due to biochar increase oxidants (electron acceptors) [14] that might inhibit or slow down the CH_4 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 CH_4 [26]. Ref. [7] reported that the CH_4 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 N_2O emission reduction, biochar could increase soil pH which favor for

the activity of N_2O 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 CH_4 emissions that found in BC as compared to BI showed that compost increase organic matter availability in soil for methane generation by methanogens.
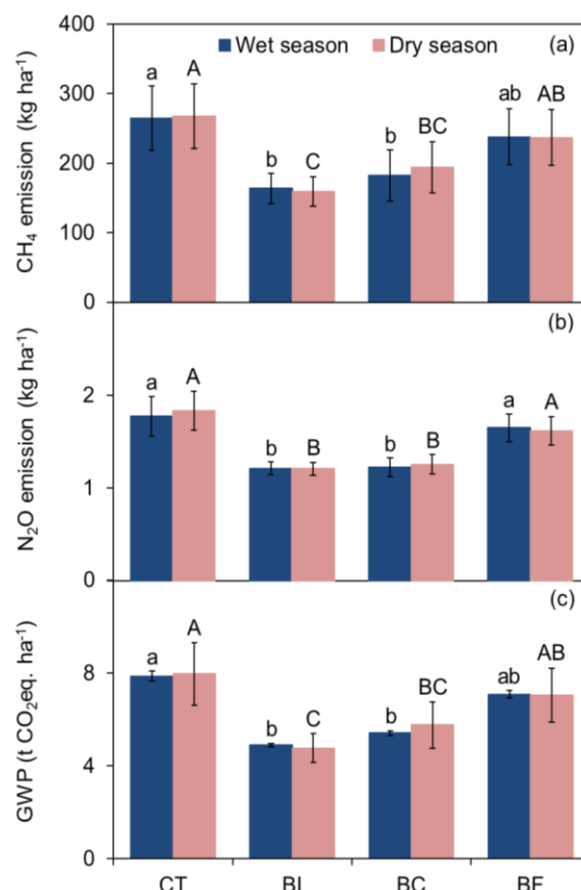

Figure 2. Cumulative seasonal CH_4 (a) and N_2O emissions (b) and GWP (c) of rice cultivation with single and co-application of biochar in wet and dry seasons.

B. Soil Properties and SOC Stock

Soil properties after two cultivation seasons were shown in Table II. It showed that all of the single application and co-applications of biochar increased soil pH, OM, C, and CEC but reduced BD after both seasons significantly. N, P and K were increased in fertilizer treatments (CT and BF) that it was significant increase in BF as compared to CT after wet season, it showed the significant potential of nutrients absorption capacity in soil as resulted of biochar. SOC stock was significantly increased in all biochar treatments due to the potential of biochar in carbon sequestration in soil. BI, BC and BF increased SOC stock by 43.7%, 46.1% and 45.3% after wet season and by 43.4%, 45.7% and 44.8% after dry season as compared to CT respectively (see Fig. 3).

Biochar has high alkalinity, resulting in increase of soil pH [28]. Increasing of OM, C and SOC stock in the soil were due to biochar contained high stabilized carbon composition and its carbon resist to biological and chemical degradation in soil as result to carbon

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].

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

| Treatment	pH (H$_2$O)	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
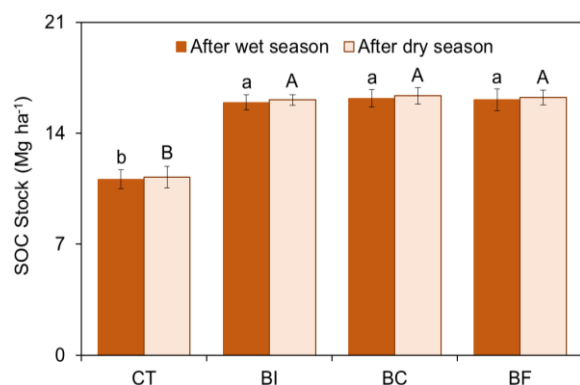
Figure 3. SOC stock after wet and dry cultivation seasons at 0-20 cm soil depth.

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].

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 CH_4 and N_2O emissions from rice cultivation with soil properties improving but its yield is unsatisfied as compared to traditional practice. When biochar was applies 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 CH_4 and N_2O 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.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

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

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