

Rice straw biochar and different urea rates on rice yield and CH₄ and CO₂ gases emissions

Lai Lai¹, Mohd Razi Ismail^{1, 2*}, Martini Mohammad Yusof², and Roslan Ismail²

¹Universiti Putra Malaysia, Institute of Tropical Agriculture and Food Security, Serdang 43400, Selangor, Malaysia.

²Universiti Putra Malaysia, Faculty of Agriculture, Serdang 43400, Selangor, Malaysia. *Corresponding author (razi@upm.edu.my).

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ABSTRACT

The application of biochar using inorganic fertilizer has been reported as being more efficient for the effective growth of soil microbes. However, there is no evidence that rice straw biochar (9 t ha⁻¹) and different urea rates have had any effect on greenhouse gas (GHG) emissions of rice (*Oryza sativa* L.) production in tropical soils. Therefore, this study was conducted to investigate the effects of urea and the application of rice straw biochar (9 t ha⁻¹) on yield and GHG emissions. Treatments were 150 kg N ha⁻¹ (T₁ control) and rice straw biochar (9 t ha⁻¹) combined with 30, 60, 90, 120, and 150 kg N ha⁻¹ (T₂, T₃, T₄, T₅, and T₆, respectively). The experiment had a randomized complete block design with four replicates. Grain yield increased 20.7% in plants grown in T₃, T₄, and T₅ compared with the control. Although all biochar treatments had increased cumulative CO₂-C emissions compared with the control (5.0% to 7.6%), the cumulative CH₄ emissions significantly decreased compared with the control (20% to 27%). Therefore, it could be suggested that T₃ and T₄ (9 t ha⁻¹ rice straw biochar with 60 and 90 kg N ha⁻¹) increase yield and reduce CH₄ emissions relative to the control. Although this study was limited to a pot experiment with no nutrient leaching, the synergetic effect of rice straw biochar (9 t ha⁻¹) and reduced urea rate is worth mentioning for acidic paddy soil; a field experiment is suggested to determine the long-term effect of biochar.

Key words: Combined effect, global warming, nitrogen fertilizer, *Oryza sativa*, rice productivity, rice straw-derived biochar.

INTRODUCTION

Flooded rice (*Oryza sativa* L.) fields are the main source of methane (CH₄) from bacterial activity under anaerobic conditions and accounts for 20% of the global warming potential (Sass et al., 2017). Babu et al. (2005) estimated that global CH₄ emissions from paddies could range from 29 to 61 t yr⁻¹ by 2020 because global rice production must almost double due to the high demand, thus leading to an increase of up to 50% in CH₄ fluxes. Carbon dioxide (CO₂) is emitted through respiration of the rice plant and from soil microorganisms (Komiya et al., 2015). The high concentration of greenhouse gases (GHG) in the atmosphere produces global warming and climate change (Nguyen, 2002).

In 2020, one of the many objectives on food security of the Malaysian government was to achieve a self-sufficient level, especially for rice, with sustainable productivity (MOA, 2010). Therefore, the impact of global warming on rice production is a vital concern (Tao et al., 2008). Kedah is one of the eight foremost rice-producing areas in Malaysia where most rice straw is burned. Gupta et al. (2004) estimated that burning rice straw produces 70% CO₂, 7% CO, 0.66% CH₄, and 2.09% N₂O.

Rice straw contains higher Si (12% to 16% > 3% to 5%) and lower lignin (6% to 7% < 10% to 12%) contents than other straw (Singh and Sidhu, 2014). After pyrolysis of the rice material at a high temperature (600 °C), the combination of Si-C bond prevents C degradation (Guo and Chen, 2014). Therefore, to manage Malaysia's sustainable rice productivity, the focus should be on improved fertilizer use efficiency through rice residue, which can possibly enhance air quality and be cost effective.

Sui et al. (2016) discovered that rice straw biochar (1.8 t ha⁻¹) and N fertilizer decreased CH₄ emissions compared with straw. Zhao et al. (2014) also reported that rice straw biochar (9 t ha⁻¹), which has a synergetic effect on soil properties with standard NPK fertilizer, increased rice yield and reduced methane gas emissions. Kamara et al. (2015) also demonstrated that rice straw biochar could improve yield through an early increase in seedling growth. However, limited evidence has so far been available for tropical soils as to the effect of rice straw biochar and different rates of N fertilizer on CH₄ and CO₂ emissions in rice production. Thus, this study aimed to investigate the reduced rate of N fertilizer through the application of rice straw biochar (9 t ha⁻¹) that can enhance yield and reduce GHG emissions.

MATERIALS AND METHODS

This pot experiment was conducted in a greenhouse (Ladang 2) at the Universiti Putra Malaysia, Serdang (3.30° N, 101.50° E; 21 m a.s.l.), Selangor on the west coast of Peninsular Malaysia. The hot humid tropical climate has high humidity and abundant rainfall.

Soil was collected from the rice (*Oryza sativa* L.) field at Kampung Padang, Teluk mukin Jeram, Tunjang, 06000 Jitra, Kedah (Peninsular Malaysia). The soil was silt loam with pH was 5.9. Soil was classified as Tropic Fluvaquent (USDA Soil Taxonomy) and Dystric Fluvisol (WRB classification) on a flat coastal plain. Parent material was likely river alluvium overlying marine alluvium.

Preparation of rice straw biochar and fertilizer

Dried rice straw was first chopped into 2.0 cm pieces and pyrolyzed in a stove under limited oxygen conditions. After filling the cylinder with pieces of rice straw, a piece of paper was placed on top of the rice straw and lit with a lighter. After burning the biomass at 500 to 700 °C for approximately 15 min and adjusting as needed, the hot biochar was immediately spread on the floor using a rolling device and cooled for approximately 1 h, providing an expected 20% granular biochar. The biochar was characterized by pH 10.08 and total C, N, and S of 24.09%, 0.60%, and 0.08%, respectively.

Fertilizer application followed the Muda Agricultural Development Authority (MADA), Malaysia, recommended rate (150 kg N ha⁻¹, 42 kg P ha⁻¹, 80 kg K ha⁻¹) for the Kedah area with split rates at 15, 35, 55, and 75 d after sowing. The N fertilizer source was a urea fertilizer and the recommended rate was reduced in the treatment at each application time, while P₂O₅ was from triple super phosphate and K₂O from muriate of potash were applied each time.

Crop establishment

Rice seeds of 'MR-288', which is one of the farmers adopted local rice varieties, were germinated in a plastic box filled with paddy soil. Plastic buckets (20 L) were filled with 15 kg air-dried soil and mixed well with water and the recommended rate of rice straw biochar (9 t ha⁻¹) in a core surface area (0.078 m² bucket surface area), except the control. After 14 d of incubation, 3 of the 2 wk-old seedlings were transplanted in each bucket in three different locations. Water was maintained as continuous flooding throughout the season.

Experimental design and treatments

The experiment was conducted using a randomized complete block design with four replicates. The detailed treatments were 150 kg N ha⁻¹ (control, T₁), rice straw biochar (9 t ha⁻¹) + 30 kg N ha⁻¹ (T₂), rice straw biochar (9 t ha⁻¹) + 60 kg N ha⁻¹ (T₃), rice straw biochar (9 t ha⁻¹) + 90 kg N ha⁻¹ (T₄), rice straw biochar (9 t ha⁻¹) + 120 kg N ha⁻¹ (T₅), and rice straw biochar (9 t ha⁻¹) + 150 kg N ha⁻¹ (T₆).

Gas sampling and analysis

The CH₄ and CO₂ fluxes were collected with closed polyvinylchloride (PVC) chambers. The PVC chamber (20 cm diameter and 120 cm height) was inserted in the soil at an approximate 5 cm depth, leaving three plants as a hill in each pot. The soil and plant temperature was measured with a thermometer probe from the hole at the top of the gas chamber. Gas sampling was performed on a biweekly interval from three replicates of each treatment between 09:00 and 11:00 h from 3 d after rice transplanting until harvest. Two samples of chamber air were taken each time at 0 and 30 min after gas chamber deployment.

The CH₄ fluxes in parts per million and CO₂ (%) were analyzed with a portable gas analyzer, non-dispersive infrared detector (PG-350E, HORIBA, Kyoto, Japan) by joining the probe of the pipe to the hole in the chamber top. Chamber air was allowed 3 min to stabilize the gas concentration at each gas sampling time. The PG-350E detector was fully calibrated at the time of manufacturing with the standard 1000 ppm CH₄ and 5% (vol) CO₂.

Estimation of sample gases

Two samples of chamber air were estimated each time by the following equation (Yang et al., 2009):

$$F = (V/A) (\Delta\text{Conc}/\Delta t)$$

where F is the methane or CO₂ or nitrous oxide emission rate (mg m⁻² h⁻¹), V is the chamber volume above the soil (m³), A is the chamber cross section (m²), ΔConc is the concentration difference between time zero and time t (mg m⁻³), and Δt is the time duration between two sampling periods (h).

The gas concentration (mg m⁻² h⁻¹) was also assumed based on the ideal gas law (PV = nRT) to provide a good gas estimate where P is pressure, V is volume, n is the number of moles, R is a gas constant, and T is temperature. Cumulative or seasonal gas emissions were estimated by the following formula (Xiang et al., 2015):

$$E = \sum_{i=1}^n (F_i + F_{i+1})/2 \times (t_{i+1} - t_i) \times 24$$

where E is cumulative gas emissions (kg ha⁻¹) and F_i and F_{i+1} are the emission rates of gas flux at time t_i and t_{i+1} (mg m⁻² h⁻¹), respectively.

Yield and yield attributes

The panicles were hand-threshed and separated into filled and unfilled grain groupings to obtain the number of grains per panicle. Panicle length was measured with a 30 cm ruler and 1000 grains were weighed. Grain yield and straw yield were also recorded from each pot of the four replicates.

Statistical analysis

Data were analyzed by two-way ANOVA using the PROC ANOVA function of the SAS v9.4 software (SAS Institute, Cary, North Carolina, USA). Treatment mean differences were compared by the least significant difference (LSD) test.

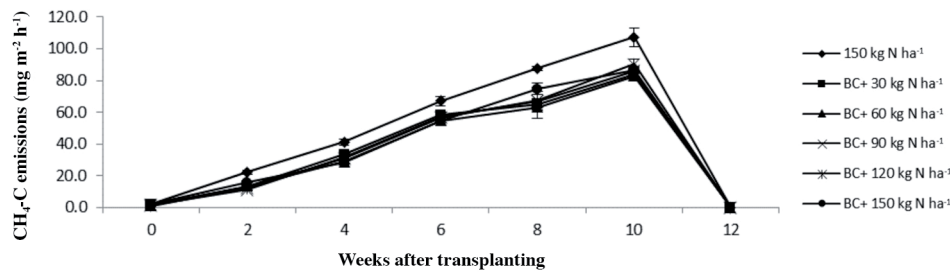
RESULTS AND DISCUSSION

Effect of rice straw biochar and N fertilizer on greenhouse gases (GHG) emissions

Methane emission. A similar trend of CH₄ fluxes was found among the treatments and a gradually increasing trend was found from week 2 to week 10 after transplanting; the maximum peak was achieved at the late grain filling stage. At week 12, CH₄ emissions from all treatments substantially decreased due to completely dry soil caused by drainage after week 10 (Figure 1). Ma et al. (2014) stated that drainage enhances soil permeability and it can retard methane-producing bacterial activity and increased CH₄ oxidation. Cumulative CH₄ emissions were significantly higher in the control than in all plants treated with biochar (Table 1). This concurs with Han et al. (2016), who found rice straw biochar and NPK fertilizer reduced CH₄ under ambient and elevated temperatures and CO₂ conditions. Previous findings of decreased CH₄ emissions in rice by applying rice straw biochar with N fertilizer (Zhao et al., 2014; Sui et al., 2016) in 2-yr rice-wheat rotation systems were also related with the results of the present study. Liu et al. (2011) suggested that the involved mechanism occurs because the increased CO₂ concentration stimulated plant growth with oxygen diffusion, which can promote CH₄ oxidation by decreasing methanogenic activity and increasing methanotrophic activity. The decreasing percentage of cumulative CH₄ emissions compared with the control treatment had values of 26.5%, 24.0%, 22.0%, 20.5%, and 19.8% in T₂, T₃, T₄, T₅, and T₆, respectively (Figure 2). There were only slight differences in the decreased percentage of cumulative CH₄ emissions compared with the control among the treatments. Therefore, the limited effect of the N fertilizer rate provided by rice straw biochar (9 t ha⁻¹) on CH₄ emissions could be clearly seen, although previously reported studies on the influences of N fertilizer on CH₄ emissions were inconsistent (Xu et al., 2016).

Carbon dioxide emissions. The pattern of CO₂ emissions in each treatment showed fluctuations that were similar to CH₄ emissions, and the maximum peaks were reached at week 10 after transplanting (Figure 3). However, the CO₂ emission rates were higher than those for CH₄. This could be due to some degree of oxidation of CH₄ into CO₂.

Figure 1. Effect of rice straw biochar and different urea rates on CH₄-C emissions.



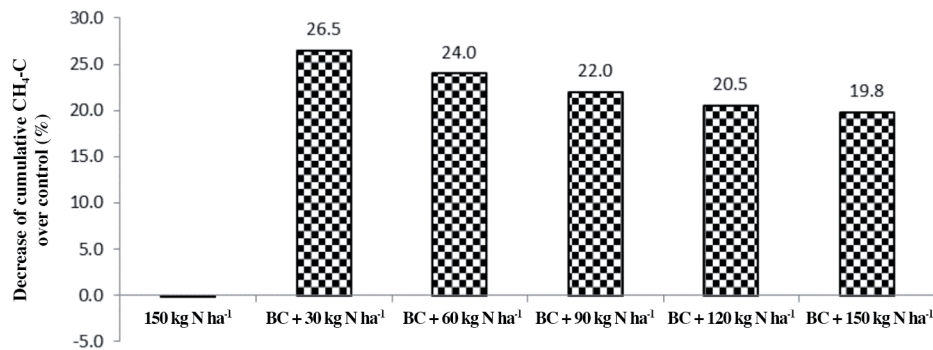
Vertical bars represent \pm standard error of mean.
BC: Rice straw biochar (9 t ha⁻¹).

Table 1. Effect of rice straw biochar (BC) and different urea rates on cumulative CH₄-C and CO₂-C emissions.

Treatments	Cumulative CH ₄ -C		Cumulative CO ₂ -C
	kg ha ⁻¹		
150 kg N ha ⁻¹	1097.3 \pm 32.59a		3885.8 \pm 67.32b
BC 9 t ha ⁻¹ + 30 kg N ha ⁻¹	806.7 \pm 18.82b		4080.3 \pm 94.49ab
BC 9 t ha ⁻¹ + 60 kg N ha ⁻¹	832.6 \pm 3.86b		4090.1 \pm 88.91ab
BC 9 t ha ⁻¹ + 90 kg N ha ⁻¹	853.2 \pm 16.83b		4177.8 \pm 52.24a
BC 9 t ha ⁻¹ + 120 kg N ha ⁻¹	869.1 \pm 32.82b		4160.3 \pm 91.43a
BC 9 t ha ⁻¹ + 150 kg N ha ⁻¹	879.3 \pm 15.77b		4118.9 \pm 101.92ab
CV, %	4.57		3.92

Means followed by the same letter within a column are not significantly different according to the LSD test (p > 0.05).
CV: Coefficient of variation.

Figure 2. Effect of rice straw biochar and different N fertilizer rates on decreased cumulative CH₄-C compared with the control.



BC: Rice straw biochar (9 t ha⁻¹).

Cumulative CO₂-C emissions had no marked differences among the biochar treatments, but T₄ and T₅ were significantly higher than the control (Table 1). Increased cumulative CO₂-C emissions compared with the control had values of 5.0%, 5.3%, 7.6%, 7.1%, and 6.2% in T₂, T₃, T₄, T₅, and T₆, respectively (Figure 4). In the present study, biochar treatments reduced cumulative CH₄ emissions from 19.8% to 26.5% compared with the control (Figure 2), but increased cumulative CO₂-C emissions from 5.0% to 7.6% compared with the control (Figure 4). The increased CO₂-C emissions in biochar treatments compared with the control were due to higher CH₄ oxidation to form CO₂. This was also reported by Karhu et al. (2011). This result concurred with Sui et al. (2016), who found that rice straw biochar at 14.8 t ha⁻¹ and 210 kg N ha⁻¹ had significantly higher total CO₂ emissions than other rice treatments. Our result was also supported by Luo et al. (2011) who estimated higher CO₂ emissions of the organic fertilizer treatment compared with other treatments and whether rice was aerobic or anaerobic. The increased CO₂-C emissions in biochar treatments compared with the control were probably due to a higher soil respiration rate with improved crop growth, which contributed to bacterial decomposition of labile C

Figure 3. Effect of rice straw biochar and different urea rates on CO₂-C emissions.

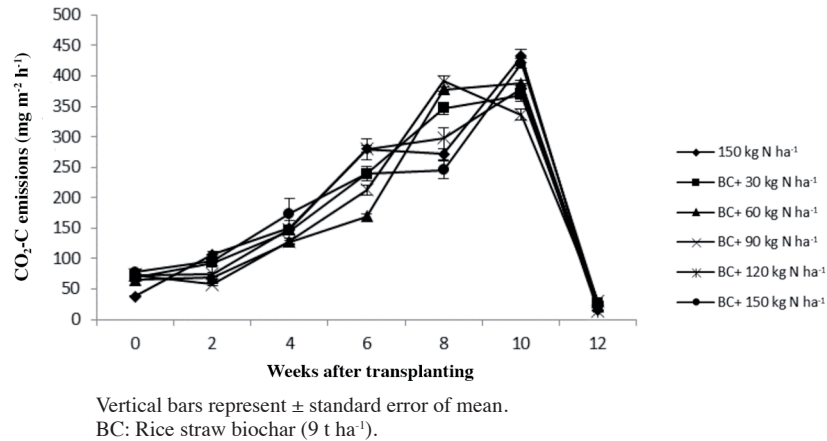
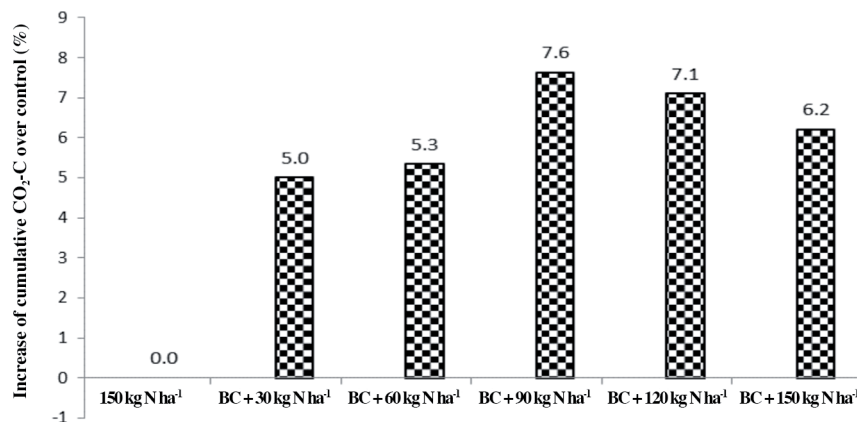


Figure 4. Effect of rice straw biochar and different urea rates on increased cumulative CO₂-C emissions compared with the control.



from rice straw biochar. Zhang et al. (2012) also reported that the application of wheat straw biochar at 40 t ha⁻¹ increased CO₂ emissions by 12% in maize with respect to N fertilizer alone due to the labile C content of biochar. A number of researchers have reported that applying biochar activated CO₂ emissions from the soil (Kuzyakov et al., 2009; Smith et al., 2010; Wang et al., 2011), and that biochar C can be lost at the same time (Luo et al., 2011). Although biochar can initially increase CO₂ emissions, Lehmann et al. (2011) pointed out that it can sequester in the soil in the long term. Liu et al. (2011) found that decreased CO₂ emissions from applying rice straw biochar rather than bamboo biochar was due to the higher pH value of rice straw biochar and because it dissolved more CO₂ in water. Meanwhile, Zhang et al. (2012), Troy et al. (2013), and Mukome et al. (2013) concluded that there was no significant effect of biochar on CO₂ emissions because there was no priming effect of biochar C and a high resistance of organic C obtained during the pyrolysis process (Jones et al., 2011; Zimmerman et al., 2011).

Effect of rice straw biochar and N fertilizer on yield and yield attributes

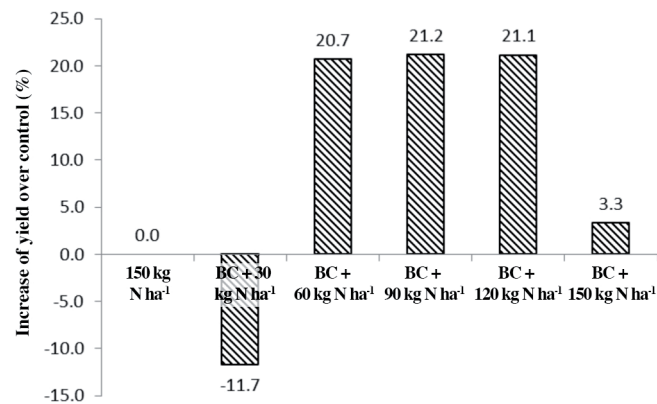
Yield attributes such as panicle length, panicle per hill, 1000 grain weight, and grain yield per hill were significantly influenced by treatments conducted on the paddy plants in the present study (Table 2). There was a slight increase in grain yield when applying biochar at approximately 3% compared with the control, but the highest straw yield occurred in T₆. Similar findings were also observed by Gebrekidan and Seyoum (2006), who found that the lowest panicle in plants with higher N had an excessive number of tillers that were not effective in improving vegetative growth and a lesser amount of carbohydrates for the developing grains. These findings concurred with Zhao et al. (2014) who found increased biomass yield of rice in the first season by seasonally adding 9.0 t ha⁻¹ rice straw biochar with a standard fertilizer. There was a

Table 2. Effect of rice straw biochar (BC) and different N fertilizer rates on yield parameters.

Treatments	Panicle length	Panicle per hill	Grains per panicle	1000 grain weight	Grain yield per hill	Straw yield per hill
	cm				g	
150 kg N ha ⁻¹	22.5bc	10.0c	66ab	23.1c	15.9c	23.4bc
BC 9 t ha ⁻¹ + 30 kg N ha ⁻¹	21.8c	9.0d	64.8b	23.9b	14.0d	21.1c
BC 9 t ha ⁻¹ + 60 kg N ha ⁻¹	22.7bc	12.0a	66.6a	24.3b	19.1a	25.0ab
BC 9 t ha ⁻¹ + 90 kg N ha ⁻¹	23.5ab	11.3b	66.9a	25.4a	19.2a	24.5ab
BC 9 t ha ⁻¹ + 120 kg N ha ⁻¹	24.5a	11.5ab	67.2a	25.9a	19.2a	25.0ab
BC 9 t ha ⁻¹ + 150 kg N ha ⁻¹	22.6bc	10.3c	66.5a	23.2c	16.4b	26.3a
CV, %	3.2	3.6	1.6	1.5	1.4	6.4

Means followed by the same letter within a column are not significantly different according to the LSD test ($p < 0.05$).

CV: Coefficient of variation.

Figure 5. Effect of rice straw biochar and different N fertilizer rates on increased yield compared with the control.

BC: Rice straw biochar (9 t ha⁻¹).

significantly higher grain yield per hill and increased yield compared with the control with values of 20.7%, 21.2%, 21.1%, and 3.3%, in T₃, T₄, T₅, and T₆, respectively (Table 2 and Figure 5). Increased grain yield could be attributed to improved soil quality (Asai et al., 2009) and increased uptake of nutrients and organic matter (Accardi-Dey and Gschwend, 2002). Yield in T₂ presumably decreased because of an inadequate amount of N fertilizer for plant uptake.

CONCLUSIONS

Although 9 t ha⁻¹ rice straw biochar + 60 kg N ha⁻¹ (treatment 3) and 9 t ha⁻¹ rice straw biochar + 90 kg N ha⁻¹ (treatment 4) had higher cumulative CO₂ (5% and 7%, respectively) in the present study, they reduced cumulative CH₄-C (24% and 22%) and increased yield (21%) compared with the control. Therefore, treatments 3 and 4 could become cultural practices to increase yield and reduce greenhouse gas emissions in the establishment of sustainable paddy production in the tropics. Although this study was limited to a pot experiment and N leaching did not occur, the application of rice straw biochar and reduced urea rates were encouraging.

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