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RESEARCH ARTICLE

Reducing methane and nitrous oxide emissions from rainfed paddy fields using corn cob-derived biochar at Central Java, Indonesia

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ABSTRACT

Rainfed paddy fields constitute approximately one-third of Indonesia's total rice (*Oryza sativa* L.) field area, including those distributed in Central Java Province. Rainfed lowlands are susceptible to the effects of climate change. Furthermore, there are several challenges in managing rainfed paddy fields, such as low crop productivity, poor soil fertility, and drought stress. Utilizing agricultural waste as biochar is expected to enhance soil quality, increase crop productivity and reduce greenhouse gas emissions responsible for global warming. The research aimed to determine the emissions of methane (CH_4) and nitrous oxide (N_2O) from rainfed paddy fields by using the corncob (*Zea mays* L.) biochar as urea coating (BCU), and biochar combined with compost. The research was conducted in rainfed paddy fields using a randomized block design with three treatments and four replicates. Plant growth, grain yield, CH_4 flux, and N_2O flux were among the parameters measured. The result showed that biochar utilization, both as a urea coating (BCU) and in combination with compost, significantly improved plant growth, increased grain yields of 'Ciherang' rice, and reduced more CH_4 and N_2O emissions in rainfed paddy fields. Grain yield increased by 29.2% with biochar-coated urea (BCU), and 11.9% with the biochar-compost combination. Furthermore, the application of biochar-compost and BCU reduced daily CH_4 flux by 93.2% and 97.7%, respectively. Compared to conventional farmer practices, biochar-compost resulted in a greater reduction in N_2O flux than BCU. Thus, utilizing agricultural waste biochar in lowland rice cultivation can increase productivity while mitigating climate change impacts.

Key words: Biochar, emission, methane, nitrous oxide, rainfed paddy fields.

INTRODUCTION

There is a significant opportunity to optimize rainfed paddy fields to bolster the national food supply. In Indonesia, rainfed areas cover 2195 million hectares, or 25.6% of the country's total paddy fields (Erythrina et al., 2021; Mulyani et al., 2022). About 33.8% of rainfed paddy fields are located in Java (distributed in Central Java, West Java, Banten, East Java), while the remainder, located outside Java, are typically cropped only once a year (Erythrina et al., 2021). Managing these fields faces several challenges, including low productivity, poor soil fertility, vulnerability to drought and climate change, and limited irrigation supplies (Erythrina et al., 2021; Al Viandari et al., 2022). Therefore, implementing appropriate, optimal, and eco-friendly management is essential to increase crop yields and soil quality, while simultaneously reducing greenhouse gas (GHG) emissions and adapting to climate change.

In 2019, Indonesia's agricultural sector contributed 105 301 Gg CO_2-e to the country's GHG emissions, representing a 24.56% increase since 2000 (Ministry of Environment and Forestry, 2021). Rice (*Oryza sativa* L.) cultivation is a major source of GHG emissions, particularly nitrous oxide (N_2O) and methane (CH_4) (Abbasi et al., 2019; Lynch et al., 2021; Tin et al., 2022), which account for 11% of agricultural N_2O emissions and 11% of anthropogenic CH_4 emissions globally (Jiang et al., 2019). Methane is produced through the anaerobic breakdown of organic matter by methanogenic microorganisms in the plant rhizosphere (Malyan et al., 2016; Tin et al., 2022). These emissions are influenced by various factors, including rice types, organic inputs, N fertilizer application, water management, and the presence of methanotrophs in the rice rhizosphere (Wang et al., 2018). Meanwhile, N_2O is generated as either a byproduct of the denitrification or an intermediate of nitrification (Adu-Poku et al., 2022; Tin et al., 2022). The N_2O emission is a form of loss of N from the soil-crop system, which results in less efficient fertilization of N into the soil. Numerous environmental issues, including N_2O emissions and inefficient N use, were brought about by the overuse of N fertilizer in agriculture (Ali et al., 2020). To mitigate these losses, the use of biochar as a urea coating has been shown to reduce N_2O emissions in dryland sorghum cultivation (Wihardjaka et al., 2025). Al Viandari et al. (2026) reported that biochar-coated urea from corncob biomass with or without microbial enrichment reduced N_2O emissions by 20.8%-40.5% and 15.3%-36.4%, respectively compared with prilled urea applied in rainfed lowland.

Lignified agricultural waste should be processed into biochar, while materials with low lignification can be composted. Biochar is a C-rich byproduct produced through the thermal degradation of organic matter at high temperatures (typically 200-500 °C) under anaerobic conditions (Haider et al., 2022; Liu et al., 2022). In general, biochar is characterized by a large specific surface area, a highly porous structure, and a high cation exchange capacity (Liu et al., 2022). Utilizing agricultural waste to create biochar, also known as bio-charcoal, can enhance soil quality and increase plant yields (Zhang et al., 2020; Haider et al., 2022). Agricultural waste is abundantly available in the agroecology of rainfed rice fields, including corncob waste. Corn (*Zea mays* L.) cobs have the potential to be used as a raw material for biochar to reduce the impact of pollution on the environment. Furthermore, biochar offers numerous benefits, including increased soil C sequestration, enhanced soil fertility, reduced GHG emissions, and improved N use efficiency, which collectively contribute to decreased fertilizer requirements (Hijbeek et al., 2019; Zhang et al., 2020; Alkharabsheh et al., 2021; Ali et al., 2022; Haider et al., 2022).

Biochar plays a crucial role in optimizing the efficiency of both inorganic and organic fertilizers. It can be used as a coating for inorganic N fertilizer or as a soil amendment combined with compost or manure. For instance, compost application ensures a steady nutrient supply while enhancing soil structure, nutrient availability, crop productivity (Wihardjaka and Harsanti, 2021). Organic fertilization using 2 t ha^{-1} straw compost has been shown to contribute approximately 50 kg K supplements per hectare (Zaini, 2017). The productivity of rainfed lowland rice, especially in Central Java Province, Indonesia, is generally not optimal, especially the yield of translating rice, which is always lower than that of direct seeded rice. Furthermore, Wihardjaka and Wade (2005) demonstrated that grain yields of minimum tillage transplanted rice (dry season) and direct-seeded rice (wet season) increased by 0.47-2.20 t ha^{-1} and 1.01-1.29 t ha^{-1}, respectively, through the application of manure-based compost.

The amount of CH_4 and N_2O gases produced and released into the atmosphere is impacted by lowland rice farmers' tendency to use imbalanced inorganic fertilizers and disregard the nutrient status of the soil. Therefore, the utilization of agricultural waste can be used for sustainable and environmentally friendly agriculture, especially for managing rainfed paddy fields. The research's goal was to use corncob charcoal to measure the CH_4 and N_2O emissions from rainfed lowland rice.

MATERIALS AND METHODS

Experimental site

The field research was conducted in rainfed paddy fields in Tlogomojo Village, Jakenan subdistrict, Pati Regency, Central Java Province. The study took place during the 2021 dry season using a transplanted rice (*Oryza sativa* L.) cropping technique. The experimental site was located at 111°10'11" E, 6°44'24" S; 12 m a.s.l. The soil is classified as an Inceptisols, characterized by very low organic C (0.66%), low levels of total N (0.11%), medium cation exchange capacity (15.99 cmol kg^{-1}). Detailed soil characteristics of the research site are presented in Table 1.

Table 1. Nutrient status before transplanting lowland rice in a rainfed rice field. [1]Criteria refer to Sulaeman et al. (2012). SiL: Silty loam.

Soil properties	Value	Status[1]
Texture:		
Sand, %	36	
Silt, %	53	
Clay, %	11	
Textural class		SiL
Available P		
Bray, mg kg^{-1}	2.80	Low
Olsen, mg kg^{-1}	10.00	Low
Available K mg kg^{-1}	15.69	Medium
Cation exchange capacity, cmol kg^{-1}	6.71	Very low
Exchangeable cations:		
K, cmol kg^{-1}	0.10	
Na, cmol kg^{-1}	0.69	Low
Ca, cmol kg^{-1}	5.89	Medium
Mg, cmol kg^{-1}	1.05	Low
Active Fe, mg kg^{-1}	0.28	Medium
Available Zn, mg kg^{-1}	0.46	
Organic C, %	0.66	Very low
Total N, %	0.11	Low
pH H_2O	6.10	Slightly neutral
Electrical conductivity, dS m^{-1}	0.78	Low

Experimental design

The study was conducted using a randomized block design with three treatments and four replicates. The treatments consisted of biochar-coated urea (BCU) (T1), biochar-compost with balanced fertilization (T2), and farmer practices without applying biochar as a control (T3). Biochar was produced via the pyrolysis of corncob biomass at a temperature of 300 °C. The corncobs were cut into small pieces (± 1-2 cm^2) and placed into a covered stainless steel. Carbonization was performed in a muffle furnace at 300 °C for 3-4 h (Harsanti et al., 2024). Biochar coating was achieved by mixing urea and biochar with molasses in a rotating granulator. For the biochar-compost treatment used a 1:1 ratio of biochar and cattle compost.

In each 625 m^2 plot, two seedlings of ‘Ciherang’ rice were transplanted at a 20 ×20 cm spacing. The total experimental area spanned 7500 m^2. The seedlings were transplanted from the nursery on 20 February 2021 and harvested on 11 May 2021. At the time of transplanting, rainfall is sufficient to saturate the soil in the planting area (Figure 1). In Figure 1, 10-days rainfall shows the amount of daily rainfall calculated in a 10 d period each month, namely the first 10-days, the second 10-days, and the third 10-days. Standard operating procedures are followed for all aspects of cultivation, including tillage, planting, crop management, harvesting, and post-harvest processing. The full amount of fertilizer/ameliorant is presented in Table 2.

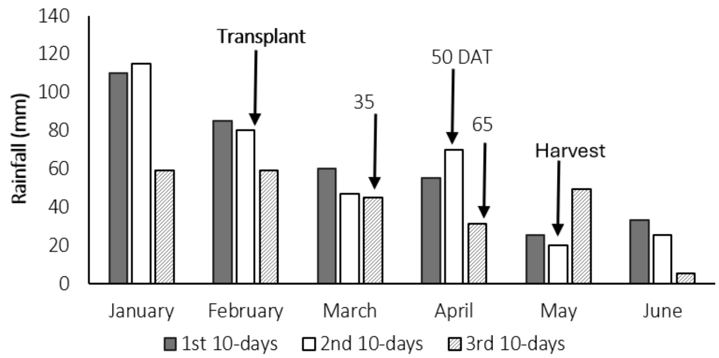

Figure 1. Ten-days rainfall distributions during the growth of 'Ciherang' rice in rainfed paddy fields, 2021. DAT: Days after transplanting; 10-days: Number of daily rainfalls calculated in a 10 d period each month.

Table 2. Fertilizer dosage used.

Treatment	Urea	BCU	NPK			KCl	Biochar-compost
			N	P_2O_5	K_2O		
	kg N ha^{-1}	kg N ha^{-1}		kg ha^{-1}		kg K_2O ha^{-1}	kg ha^{-1}
Biochar-coated urea (BCU)	-	100	40	40	40	20	-
Biochar-compost	80	-	40	40	40	20	5000
Farmers practices	112	-	45	45	45	-	-

In the T1 treatment, NPK fertilizer (15% N, 15% P_2O_5, 15% K_2O) was applied at transplanting, while BCU and KCl (60% K_2O) were applied at 21 d after transplanting (DAT). In the T2 treatment, NPK and biochar-compost were applied at transplanting, while urea and KCl were applied in two equal splits (½ dose each) at 21 and 42 DAT. In the treatment of farmer practices (T3), NPK and urea fertilizers were applied following local habits without the addition of manure or biochar. Both fertilizers were applied in two splits at 21 and 42 DAT. The content of C and N in biochar-compost is presented in Table 3.

Table 3. Content of organic C and total N in biochar-compost. [1]Criteria refer to Sulaeman et al. (2012).

Variables	Value	Status[1]
Organic C, %	15.24	Very high
Total N, %	1.27	Very high
C/N ratio	12	

Parameters observed and data analysis

Environmental factors (N_2O and CH_4 fluxes) and agronomic factors (grain yield, plant height, and tiller number) were among the characteristics that were noted. Twenty hills were used to randomly measure the number of tillers and plant height. Grain yield was determined from a 10 × 10 m harvest area, with grain moisture content recorded at harvest.

Gas sampling was taken three times, namely at 35, 50, and 65 DAT when the soil moisture condition was saturated with water (Figure 1). Gas samples were collected using the closed-chamber method following the procedures described by Ariani et al. (2016). Closed chambers with dimensions of 40 cm × 40 cm base × 100 cm height (for CH_4) and 20 cm × 40 cm base × 30 cm height (for N_2O) were used to gather air samples. The chamber was placed over and enclosed four rice clumps during air sampling for CH_4, while the chamber for N_2O air sampling was placed between the rows of rice clumps. Air samples were taken at critical growth stages. After closing the chamber, 10 mL gas samples were collected using syringes at 5, 10, 15, and 20 min intervals.

To measure the amounts of GHG, the air samples were put into a gas chromatograph that had an electron capture detector for N_2O and a flame ionization detector for CH_4. The GHG fluxes were computed using the following formula, which was employed by Ariani et al. (2016):

$$E = \rho \times \frac{V}{A} \times \frac{\Delta c}{\Delta t} \times \frac{273}{(273 + T)} \quad \text{......................................} (1)$$

where E is flux of CH_4 or N_2O (mg m^{-2} h^{-1}), ρ is density of CH_4 or N_2O, V is volume of chamber (m^3), A is surface area of chamber (m^2), Δc/Δt is gas rate per time, T is average temperature inside chamber (°C).

Data were statistically analyzed using SPSS v22 statistical program (IBM, Armonk, New York, USA), including ANOVA followed by the Tukey's honest significant difference (HSD) test at a 5% probability level to identify significant differences between treatment means.

RESULTS AND DISCUSSION

Rice growth and yield

Plant height before harvest, as well as maximum and productive tillers, were higher in biochar-treated plots than in farmer practice plots ($p < 0.05$; Table 4). Biochar used as a urea coating was not significantly different from biochar combined with compost on the growth parameters of the 'Ciherang'.

The yield of milled dry unhusked rice (14% moisture content) was higher with biochar application than without biochar ($p < 0.05$; Table 4). Utilization of biochar increased grain yield by 29.26% (urea coating) and 11.87% (combined with compost), respectively (Table 4). Coating urea with biochar makes the fertilizer a slow-decomposing N fertilizer, allowing the rice plants to utilize the nutrient effectively for growth and development. Using biochar as a urea coating (BCU) was significantly more effective in increasing 'Ciherang' rice grain yields in rainfed areas than applying biochar combined with compost.

Table 4. 'Ciherang' rice growth and grain yield during the 2021 dry season. Means in a column followed by the same letter are not significantly different according to the Tukey's HSD test ($p \leq 0.05$). *Significant at $p < 0.05$.

Treatments	Plant height	Tiller number per hill		Grain yield 14% MC	Yield difference	Yield increase
		Maximum	Productive			
	cm			kg ha^{-1}	kg ha^{-1}	%
Biochar-coated urea (BCU)	107.4^{a}	20.1^{a}	11.9^{a}	4161^{a}	942	29.26
Biochar-compost	103.4^{ab}	19.9^{a}	11.2^{a}	3601^{ab}	382	11.87
Farmer practices	102.3^{b}	14.9^{b}	9.1^{b}	3219^{b}		
p-value	*	*	*	*		

Flux of methane and nitrous oxide

Rainfed paddy fields under farmer practices produced higher fluxes significantly than those treated with neither BCU nor biochar-compost (Figure 2). Daily CH_4 fluxes decreased with the growth phase of the plants, especially in the BCU and biochar-compost treatments. In contrast, CH_4 emissions in the farmer practices (without biochar) increased again at 65 d after transplanting (DAT). Daily CH_4 fluxes ranged from 13.6 to 750.5 mg CH_4 m^{-2} d^{-1} in biochar-compost plots and 4.6 to 493.4 mg CH_4 m^{-2} d^{-1} in BCU plots, whereas farmer practices plots exhibited higher ranges from 200.6 to 827.2 mg CH_4 m^{-2} d^{-1}. Biochar application, either combined with compost or used as a urea coating, reduced daily CH_4 flux by 9.2%-93.2% and 37.9%-97.7%, respectively, relative to farmer practices.

Table 5 shows that CH_4 emissions were the highest in the farmer practice plots compared to those in the biochar-compost and BCU plots. Westphal et al. (2018) showed that long-term application of organic fertilizers can enhance soil respiration, C absorption, N mineralization potential, and ammonium oxidation potential. Beyond mitigating waste management issues and supplying soil nutrients, organic fertilizers contribute to climate change mitigation by sequestering or absorbing C. In contrast, inorganic fertilizer application may accelerate organic matter decomposition and diminish aggregate stability (Zhao et al., 2020). The effects of inorganic fertilizers on CH_4 emissions remain a subject of debate in the literature. According to Wang et al. (2018), while some studies indicate that inorganic fertilizers reduce CH_4 emissions, others show an increase or nonsignificant change. Furthermore, they reported that methanotrophic microbes can stimulate CH_4 emissions reduction in the rhizosphere of paddy soil under an intermittent water regime.

Table 5. Emissions of methane and nitrous oxide, and global warming potential (GWP) from rainfed paddy fields applied with corn waste biochar. Means in a column followed by the same letter are not significantly different according to the Tukey's HSD test ($p \leq 0.05$). **Significant at $p < 0.01$.

Treatments	CH_4 emission	N_2O emission	GWP	Emission index
	kg ha^{-1} season^{-1}	g ha^{-1} season^{-1}	kg CO_2-e ha^{-1} season^{-1}	kg CO_2-e kg^{-1} grain
Biochar-coated urea (BCU)	47^{c}	24.9^{a}	1176^{c}	0.33^{b}
Biochar-compost	69^{b}	22.3^{a}	1723^{b}	0.43^{b}
Farmer practices	176^{a}	17.4^{b}	4403^{a}	1.32^{a}
p-value	**	**	**	**

The rainfed paddy fields with BCU produced a higher N_2O flux than those under biochar-compost application and farmer practices (Figure 3). Daily N_2O flux at 65 DAT was higher than at 50 DAT and 35 DAT. Daily N_2O fluxes ranged from 108.0 to 972.7 µg N_2O m^{-2} d^{-1} in biochar-compost plots, and 152.9 to 1825.3 µg N_2O m^{-2} d^{-1} in BCU plots, while farmer practice plots yielded 37.7 to 1954.2 µg N_2O m^{-2} d^{-1}. Daily N_2O flux in BCU plots was higher than farmer practices plots, especially at 50 DAT and 65 DAT. Compared to farmer practices, biochar combined with compost resulted in a greater average reduction of N_2O flux than BCU.

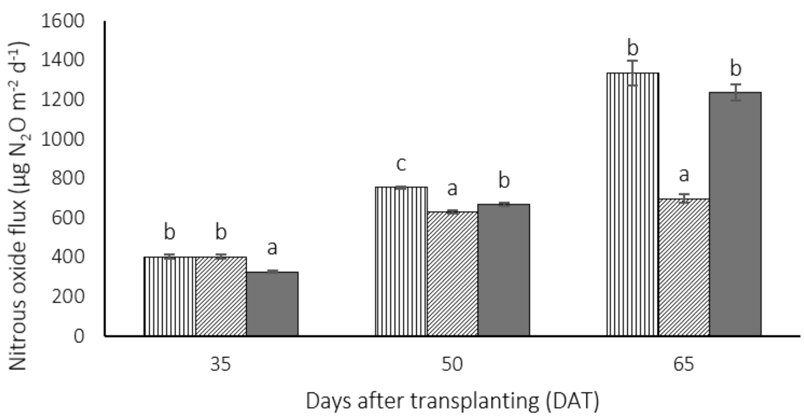

Figure 3. Nitrous oxide flux from rainfed paddy fields applied with corn waste biochar. Vertical bars correspond to standard error. Each time observation, bars followed by the same letter are not significantly different according to the Tukey's HSD test (p ≤ 0.05).

Table 5 shows that the N_2O emissions in the BCU plots were the highest among all treatments. Furthermore, N_2O emissions increased as rice plants matured in nearly every observation. According to Baruah et al. (2016), root exudates, which increase alongside plant growth, influence the concentration of dissolved organic C (DOC) in the rice rhizosphere. Furthermore, an accumulation of plant residues increases DOC levels, subsequently enhancing N_2O emissions. In a related study, Westphal et al. (2018) investigated N_2O flux in agricultural soil treated with both synthetic and organic fertilizers. They found that the cumulative value of N_2O flux was higher in soils treated with synthetic fertilizers than in those treated with organic fertilizers. However, Westphal et al. (2018) suggested that prolonged application of organic fertilizers may eventually stimulate N_2O emissions due to the organic fertilizers' slow release of N minerals, which gradually increase soil N levels and soil organic matter concentrations.

Farmer practices without using biochar resulted in a higher global warming potential (GWP) than treatments using biochar-compost and BCU (Table 5). Accordingly, biochar contributes significantly to the reduction of greenhouse gas emissions (Ayaz et al., 2023). Similarly, the emission index for farmer practices was higher in greenhouse gas (GHG) emissions than biochar-compost and BCU (Table 5). The use of biochar can help reduce GHG emissions from soil and improve soil quality for plant growth, but its efficacy depends on various factors such as soil type, environmental conditions, and application method. Therefore, integrating biochar is a crucial consideration for sustainable farming practices.

CONCLUSIONS

The utilization of corn waste biochar, either as a urea coating or in combination with compost, significantly improves plant growth, and grain yields for 'Ciherang' rice. Furthermore, it reduces methane (CH_4) and nitrous oxide (N_2O) emissions, resulting in lower global warming potential values compared to without biochar as in farmer practices in rainfed paddy fields. Corn cob derived biochar increased 'Ciherang' rice yields by 29.2% when used as a urea coating and by 11.9% when combined with compost. Compared to farmer practices, the application of biochar-compost or biochar-coated urea (BCU) reduced daily CH_4 flux by 93.2% and 97.7%, respectively. Furthermore, the application of biochar combined with compost reduced N_2O flux on average higher than BCU.

Author contribution

Conceptualization: A.W., E.S.H., M.T.S. Methodology: A.W., E.S.H., T.A.A., Y.H., B.N. Software: A.W., U.S.S. Validation: A.W. Formal analysis: A.W., U.S.S. Investigation: T.A.A., E.S.H., Y.H., B.N., U.S.S. Resources: A.W. Data curation: A.W., E.S.H. Writing-original draft: A.W., E.S.H., T.A.A., B.N., Y.H., U.S.S. Writing-review & editing: A.W., E.S.H., M.T.S. Visualization: A.W., U.S.S. Supervision: A.W. Project administration: E.S.H. Funding acquisition: T.A.A. All co-authors reviewed the final version and approved the manuscript before submission.

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References

Abbasi, T., Abbasi, T., Luithui, C., Abbasi, S.A. 2019. Modelling methane and nitrous oxide emissions from rice paddy wetlands in India using Artificial Neural Networks (ANNs). Water 11(10):2169. doi:10.3390/w11102169.

Adu-Poku, D., Ackerson, N.O.B., Devine, R.N.O.A., Addo, A.G. 2022. Climate mitigation efficiency of nitrification and urease inhibitors: Impact on N_2O emission–A review. Scientific African 16:e01170. doi:10.1016/j.sciaf.2022.e01170.

Al Viandari, N., Adriany, T.A., Zu'amah, H., Harsanti, E.S., Wihardjaka, A., Supriyo, A., et al. 2026. Effect of biochar-coated urea and manure on N_2O and CO_2 flux dynamics during sorghum growth in rainfed fields. Chilean Journal of Agricultural Research 86:439-448. doi:10.4067/S0718-58392026000300439.

Al Viandari, N., Wihardjaka, A., Pulunggono, H.B., Suwardi. 2022. Sustainable development strategies of rainfed paddy fields in Central Java, Indonesia: A review. Caraka Tani: Journal of Sustainable Agriculture 37(2):275-288. doi:10.20961/carakatani.v37i2.58242.

Ali, I., Adnan, M., Iqbal, A., Ullah, S., Khan, M.R., Yuan, P., et al. 2022. Effects of biochar and nitrogen application on rice biomass saccharification, bioethanol yield and cell wall polymers features. International Journal of Molecular Sciences 23(21):13635. doi:10.3390/ijms232113635.

Ali, I., Ullah, S., He, L., Zhao, Q., Iqbal, A., Wei, S., et al. 2020. Combined application of biochar and nitrogen fertilizer improves rice yield, microbial activity and N-metabolism in a pot experiment. PeerJ 8:e10311. doi:10.7717/peerj.10311.

Alkharabsheh, H.M., Seleiman, M.F., Battaglia, M.L., Shami, A., Jalal, R.S., Alhammad, B.A., et al. 2021. Biochar and its broad impacts in soil quality and fertility, nutrient leaching and crop productivity: A review. Agronomy 11(5):993. doi:10.3390/agronomy11050993.

Ariani, M., Hervani, A., Setyanto, P. 2016. N_2O emission from managed soil under different crops in rainfed area, Central Java. Journal of Tropical Soils 21(2):79-89. doi:10.5400/jts.2016.v21i2.79-89.

Ayaz, M., Feizienė, D., Tilvikienė, V., Feiza, V., Baltrėnaitė-Gedienė, E., Ullah, S. 2023. Biochar with inorganic nitrogen fertilizer reduces direct greenhouse gas emission flux from soil. Plants 12(5):1002. doi:10.3390/plants12051002.

Baruah, A., Bordoloi, N., Baruah, K.K. 2016. Effect of organic amendments with varied C-N ratios on grain productivity and nitrous oxide (N_2O) emission from wheat grown in alluvial soil. Australian Journal of Crop Science 10(4):460-469. doi:10.21475/ajcs.2016.10.04.p6970x.

Erythrina, E., Anshori, A., Bora, C.Y., Dewi, D.O., Lestari, M.S., Mustaha, M.A., et al. 2021. Assessing opportunities to increase

yield and profit in rainfed lowland rice systems in Indonesia. Agronomy 11(4):777. doi:10.3390/agronomy11040777.
Haider, F.U., Coulter, J.A., Cai, L., Hussain, S., Cheema, S.A., Wu, J., et al. 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.
Harsanti, E.S., Ardiwinata, A.N., Sukarjo, Zu'amah, H., Kurnia, A., Sutriadi, M.T., et al. 2024. Nitrogen losses (N_2O and NO_3^-) from mustard (*Brassica juncea* L.) cropping applied urea coated bio-charcoal. Plant, Soil and Environment 70(1):1-10. doi:10.17221/282/2023-PSE.
Hijbeek R, van Loon MP, van Ittersum MK. 2019. Fertiliser use and soil carbon sequestration: opportunities and trade-offs. CCAFS Working Paper N°264. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Wageningen, The Netherlands.
Jiang, Y., Carrijo, D., Huang, S., Chen, J., Balaine, N., Zhang, W., et al. 2019. Water management to mitigate the global warming potential of rice systems: A global meta-analysis. Field Crops Research 234:47-54. doi:10.1016/j.fcr.2019.02.010.
Liu, Y., Li, H., Hu, T., Mahmoud, A., Li, J., Zhu, R., et al. 2022. A quantitative review of the effects of biochar application on rice yield and nitrogen use efficiency in paddy fields: A meta-analysis. Science of the Total Environment 830:154792. doi:10.1016/j.scitotenv.2022.154792.
Lynch, J., Cain, M., Frame, D., Pierrehumbert, R. 2021. Agriculture's contribution to climate change and role in mitigation is distinct from predominantly fossil CO_2-emitting sectors. Frontiers in Sustainable Food Systems 4:518039. doi:10.3389/fsufs.2020.518039.
Malyan, S.K., Bhatia, A., Kumar, A., Gupta, D.K., Singh, R., Kumar, S.S., et al. 2016. Methane production, oxidation and mitigation: A mechanistic understanding and comprehensive evaluation of influencing factors. Science of the Total Environment 572:874-896. doi:10.1016/j.scitotenv.2016.07.182.
Ministry of Environment and Forestry. 2021. Indonesia submission on the document of updated nationally determined contribution (NDC) and document of long-term strategy on low carbon and climate resilience 2050. Ministry of Environment and Forestry, Jakarta, Indonesia.
Mulyani, A., Mulyanto, B., Barus, B., Panuju, D.R., Husnain. 2022. Analysis of rice field production capacity for national food security by 2045. Jurnal Sumberdaya Lahan 16(1):33-50. doi:10.21082/jsdl.v16n1.2022.33-50.
Sulaeman, Suparto, Eviati. 2012. Petunjuk teknis analisis kimia tanah, tanaman, air dan pupuk. In Balai Penelitian Tanah. Balai Penelitian Tanah. Available at https://tanahpupuk.bsip.pertanian.go.id
Tin, M.T., Chidthaisong, A., Pumijumnong, N., Arunrat, N., Yuttitham, M. 2022. Methane and nitrous oxide emissions from lowland rice as affected by farmers' adopted fertilizer applications under two crop establishment methods in Myanmar. Environment and Natural Resources Journal 20(6):621-633. doi:10.32526/ennrj/20/202200095.
Wang, J., Akiyama, H., Yagi, K., Yan, X. 2018. Controlling variables and emission factors of methane from global rice fields. Atmospheric Chemistry and Physics 18:10419-10431. doi:10.5194/acp-18-10419-2018.
Westphal, M., Tenuta, M., Entz, M.H. 2018. Nitrous oxide emissions with organic crop production depends on fall soil moisture. Agriculture, Ecosystems and Environment 254:41-49. doi:10.1016/j.agee.2017.11.005.
Wihardjaka, A., Al Viandari, N., Adriany, T.A., Zu'amah, H., Harsanti, E.S., Supriyo, A., et al. 2025. Effect of organic amendment and biochar-coated urea on sorghum yield, nitrogen use efficiency, and soil water infiltration in rainfed lowland. Chilean Journal of Agricultural Research 85:650-660. doi:10.4067/S0718-58392025000500650.
Wihardjaka, A., Harsanti, E.S. 2021. Management of environmentally friendly rice field by means of organic fertilizer utilization to improve soil quality. Pangan 30(1):53-64. doi:10.33964/jp.v30i1.496.
Wihardjaka, A., Wade, L.J. 2005. Nutrient by water interactions in rainfed lowland rice at different positions in the toposequence. Penelitian Pertanian Tanaman Pangan 24(2):85-96.
Zaini, Z. 2017. Pupuk majemuk dan pemupukan hara spesifik lokasi pada padi sawah. Iptek Tanaman Pangan 7(1):1-7. Available at http://webapps.irri.org/nm/id.
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(8):3436. doi:10.3390/SU12083436.
Zhao, Z., Zhang, C., Li, F., Gao, S., Zhang, J. 2020. Effect of compost and inorganic fertilizer on organic carbon and activities of carbon cycle enzymes in aggregates of an intensively cultivated Vertisol. PLOS ONE 15(3):e022964. doi:10.1371/journal.pone.0229644.