







Effect of biochar-coated urea and manure on N₂O and CO₂ flux dynamics during sorghum growth in rainfed fields

Nourma Al Viandari¹, Terry Ayu Adriany¹, Hidayatuz Zu'amah², Elisabeth Srihayu Harsanti^{2*}, Anicetus Wihardjaka^{1*}, Agus Supriyo¹, Ety Pratiwi¹, I Gusti Made Subiksa³, Wahida Annisa Yusuf³, and Cahyoadi Bowo⁴

¹National Research and Innovation Agency (BRIN), Research Center for Food Crops, Cibinong 16915, West Java, Indonesia.

²National Research and Innovation Agency (BRIN), Research Center for Horticulture, Cibinong 16915, West Java, Indonesia.

³Ministry of Agriculture, Jl. Harsono, Pasar Minggu, Jakarta, Indonesia.

⁴Jember University, Agricultural Faculty, Jember, East Java, Indonesia.

*Corresponding author (esharsanti@gmail.com; awihardjaka@gmail.com)

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ABSTRACT

Rainfed land in Indonesia is vulnerable to the impacts of climate change and is constrained by low soil fertility. External inputs such as biochar-coated urea and livestock manure can reduce greenhouse gas emissions from rainfed land, particularly nitrous oxide (N₂O) and carbon dioxide (CO₂). Anthropogenic CO₂ and N₂O emissions from rainfed fields contribute to global warming. The research aims to determine the effect of urea-coated biochar-enriched consortia microbes and manure on flux dynamics of CO₂ and N₂O under sorghum growth (*Sorghum bicolor* [L.] Moench) in a rainfed field. A field experiment was conducted using a two-factor randomized complete block design with three replicates and two-factor treatments. The three levels of first factor treatment were no manure, cow manure, chicken manure, and the four levels of second factor treatment was farmer's recommended dose, prilled urea, biochar-coated urea, biochar-coated urea with microbial enrichment. Observed parameters included plant height, biomass yield, N₂O flux, and CO₂ flux. Only manure application significantly affected plant height, but its interaction with N input was nonsignificant for either plant height or sorghum biomass yield. The N₂O flux pattern is high at the beginning of sorghum growth and decreases towards harvest, while the CO₂ flux pattern is irregular. Manure treatment and N input significantly affect N₂O emissions, but not CO₂ emissions. Biochar-coated urea from corn biomass, either without or with microbial enrichment, can reduce N₂O emissions by 20.8%-40.5% or 15.3%-36.4%, respectively. The combination of biochar-based fertilizer with organic manure can potentially mitigate greenhouse gas emissions in rainfed fields.

Key words: Carbon dioxide flux, nitrous oxide flux, prilled urea, rainfed fields, *Sorghum bicolor*, sorghum growth, urea-coated biochar.

INTRODUCTION

Indonesia is promoting alternative food sources, such as those beyond rice and corn, to achieve sustainable food security. Rice paddies have traditionally been the primary source of food security. However, the shrinking area of rice paddies due to annual land conversion has encouraged the optimization of dryland utilization for the cultivation of cereal crops other than rice and corn, namely sorghum. Dryland in Indonesia is quite extensive, namely, more than 144 million hectares (Hikmat et al., 2022; Yusuf et al., 2024). Some of which have the potential to be used as land for cultivating food crops (more than 20%), especially rainfed fields. However,

dryland is constrained by its vulnerability to the impacts of climate change and low nutrient availability. One alternative food crop that is adaptive to the impacts of climate change, especially in rainfed areas, is sorghum.

Sorghum (*Sorghum bicolor* [L.] Moench) is a climate-resilient crop to suboptimal conditions, including drought, waterlogging, and pest pressure (Khalifa and Eltahir, 2023). It thrives in dryland and rainfed agroecosystems (Hazmi et al., 2022; Sahara et al., 2023), making it a strategic crop in suboptimal regions. Sorghum's stems serve as raw material for ethanol, while the leaves and grains are valuable for animal feed and human consumption. It makes sorghum a significant value due to its diverse uses (de Morais Cardoso et al., 2017; Dwipajati et al., 2022). Better growth and development of sorghum plants is determined by the availability of nutrients supplied from inorganic N fertilizers and organic materials.

Nitrogen is one of the essential nutrients needed for the growth and development of sorghum plants. Nitrogen is vital for plant growth and functions in amino acid synthesis, photosynthesis, and chlorophyll production (Fathi, 2022). Depending on soil conditions, it is typically absorbed as ammonium (NH_4^+) or nitrate (NO_3^-). Urea is a widely used N source; however, its efficiency is often low due to losses via volatilization, leaching, and denitrification. These losses are particularly pronounced in aerobic soils where nitrous oxide (N_2O) is emitted (Ma et al., 2019; Mahmud et al., 2021). Studies estimate that only 20%-30% of applied N is utilized by crops, while 50%-55% is lost to the environment (Cheng-Fang et al., 2012; Geng et al., 2017).

The biochar-coated urea is one strategy to reduce greenhouse gas emissions and can also improve N use efficiency in rainfed fields. Biochar, a C-rich material from biomass pyrolysis, acts as a slow-release carrier for nutrients and improves soil structure, moisture retention, and microbial activity (Mahmud et al., 2021; Lenka et al., 2022). Combined with organic inputs like manure and beneficial microbes, it can further boost nutrient availability and reduce N losses (Adhikari et al., 2022; Govindasamy et al., 2023). Moreover, biochar-coated urea which is combined with organic input such as manure also provided beneficial effect on sorghum growth and yield, approximately 7.5%-8.9% higher compared to treatments without manure application (Wihardjaka et al., 2025).

External inputs on rainfed fields may influence the dynamics of greenhouse gas fluxes, especially N_2O and CO_2 , due to alternating wet-dry soil conditions. Nitrous oxide is an intermediate product of the nitrification-denitrification process, while CO_2 is a product of the decomposition of organic matter in the soil (Sun et al., 2024). Agricultural soils contribute as much as 53% N_2O , 35% CO_2 , and 47% CH_4 emissions, significantly contributing to global warming potential (GWP) (Basheer et al., 2024). The GWP of N_2O is 296-310 times more potent than CO_2 (Basheer et al., 2024; Wang et al., 2025). In comparison to the pre-industrial era, the current atmospheric concentrations of CO_2 , CH_4 , and N_2O are 409, 1.862, and 0.329 mg kg^{-1} , respectively, with growth rates of 143%, 254%, and 122% (Padhi et al., 2024).

Despite the promising role of biochar and organic amendments, limited research has explored their combined effects on greenhouse gas emissions and sorghum performance in rainfed lowlands. Therefore, the research aims to determine the effect of urea-coated biochar-enriched consortia microbes and manure on the flux dynamics of CO_2 and N_2O under sorghum growth in a rainfed field. The goal strengthens sustainable fertilization practices that enhance crop productivity while mitigating climate change impact.

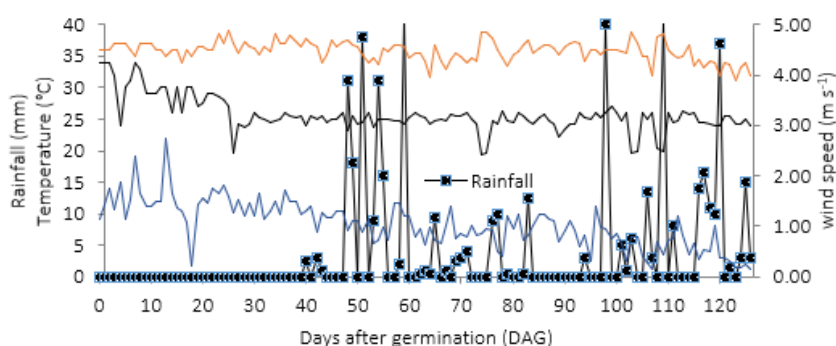
MATERIALS AND METHODS

Experimental site and soil analysis

A field experiment was conducted during the third growing season from September to December 2023 in Jaken rainfed rice fields (6°46'33" S, 111°11'44" E), Pati regency, Central Java province, Indonesia. The soil type at the study location is classified as Typic Endoaquepts, with soil characteristics and analytical methods presented in Table 1. The Typic Endoaquepts with silty clay loam texture have moderately acidic (pH- H_2O 5.54), low organic C (0.31%) and total N (0.41%), indicating poor soil fertility. Although the soil has relatively high available P (140.9 mg kg^{-1}) and K (103.6 mg kg^{-1}), it has a moderate cation exchange capacity (CEC) (17.09 $\text{cmol}_{(+) } \text{kg}^{-1}$), limiting nutrient retention. Rainfall intensity during the experiment is presented in Figure 1.

Table 1. Soil properties in the experimental site. CEC: Cation exchange capacity.

Soil properties	Analytical method	Value
pH H ₂ O (1:2.5)	Electrode, pH-metric	5.54
Organic C, %	Walkley & Black	0.31
Total N, %	Kjeldahl	0.41
P ₂ O ₅ , mg kg ⁻¹	Extracted HCl 25%	140.90
K ₂ O, mg kg ⁻¹	Extracted HCl 25%	103.60
CEC, cmol ₍₊₎ kg ⁻¹	Saturation NH ₄ OAc pH 7	17.09
Exchangeable K, cmol ₍₊₎ kg ⁻¹	Saturation NH ₄ OAc pH 7	0.04
Exchangeable Na, cmol ₍₊₎ kg ⁻¹	Saturation NH ₄ OAc pH 7	0.09
Exchangeable Ca, cmol ₍₊₎ kg ⁻¹	Saturation NH ₄ OAc pH 7	8.83
Exchangeable Mg, cmol ₍₊₎ kg ⁻¹	Saturation NH ₄ OAc pH 7	0.25
Texture:	Pipette	Silty clay loam
Sand, %		21
Silt, %		44
Clay, %		35

**Figure 1.** Distribution of rainfall, temperature, and wind speed during a growing season in the experimental site.

Experimental design

A randomized complete block design (RCBD) was used with three replicates and two factors, totaling 36 plots. The first factor was manure, comprising: Without manure (A1), cow manure (A2), and chicken manure (A3). The second factor was N-urea input treatment, which included: Farmer's recommended dose (P1), prilled urea (P2), biochar-coated urea (P3), biochar-coated urea with microbial enrichment (P4). According to the recommendation of the Directorate General of Food Crops, Ministry of Agriculture of Indonesia, manure was applied at 2 t ha⁻¹ (dry weight). Treatment of farmers' practice uses 130 kg N-urea ha⁻¹, while the dosage for treatments P2, P3, and P4 is 90 kg N ha⁻¹.

Cultural practices

The microbial consortium that enriched the biochar-coated urea consisted of *Bacillus aryabhatai* 32, *B. marisflavi* 7, and *B. aerius* 21. These strains possess N-fixing and P-solubilizing capabilities and are tolerant to abiotic stress (drought and salinity). Each strain was cultured in LB liquid medium to reach a population of 10⁹ cell-forming units (CFU) per mL, centrifuged at 5000 rpm for 5 min, and resuspended in physiological saline.

Biochar-coated urea was prepared using a urea-to-biochar ratio of 80:20. A mixture of 40 mL bacterial suspension (10⁹ CFU mL⁻¹) was sprayed onto 1 kg coated urea. The product was then air-dried to its original moisture level before application. The biochar used as a urea coating has a pH-H₂O of 10.48 and contains 0.91%

N, 2.31% P₂O₅, and 0.01% K₂O. The microbial population of the consortium in biochar-coated urea was able to survive, and after 3 mo storage, it only decreased by around 1.9%-2.9%.

The soil was tilled once, leveled, and platted as experimental units. Manure from livestock was incorporated into the soil 2 wk before the sorghum seedlings were planted. The cow manure used had a pH of 7.14 and contained 21.72% organic C, 0.75% N, 22.4 mg P₂O₅ kg⁻¹, and 11.7 mg K₂O kg⁻¹, while chicken manure had a pH of 5.19 and contained 22.19% organic C, 0.92% N, 49.7 mg P₂O₅ kg⁻¹, and 3.4 mg K₂O kg⁻¹. According to the minimum technical requirements set by the Decree of the Minister of Agriculture of the Republic of Indonesia No. 261/2019, the cow and chicken manure used in this study met the criteria for soil ameliorants, with organic C content exceeding 15% and a C/N ratio within an acceptable range of 15-25.

The seedling of a local sorghum (*Sorghum bicolor* [L.] Moench) variety was planted with a spacing of 70 cm × 30 cm in 5 m × 4 m plots. Fertilizer rates were 90 kg N ha⁻¹ applied in three splits at 7, 14, and 30 d after germination (DAG), 36 kg P₂O₅ ha⁻¹ applied once at 7 DAG, 30 kg K₂O ha⁻¹ applied twice at 7 and 30 DAG. Crop management included routine weed and pest control. Sorghum plants are harvested when the biomass is still greenish.

Data collection and analysis

Parameters measured included initial soil properties, plant agronomic variables (plant height, dry biomass yield), nitrous oxide (N₂O) flux, and carbon dioxide (CO₂) flux. The plant height was observed from eight randomly selected plants per plot at harvesting time. The biomass yield was measured from an area harvest of 2.8 m × 2.2 m in each plot. All soil and gas analyses were performed at the Indonesian Agricultural Environment Instrument Standard Testing Institute (IAESTI) at Pati, Central Java province.

Gas samples were collected using a closed acrylic chamber (40 cm × 20 cm base × 30 cm height) at 15, 25, 45, 95, and 125 d after germination (DAG). At each interval, 20 mL gas was collected at 10, 20, 30, and 40 min, with temperature recorded concurrently. The chamber base remained fixed during the entire sampling period. Samples were stored in vials and analyzed for N₂O and CO₂ using a gas chromatograph with an electron capture detector (ECD) and thermal conductivity detector (TCD) (14B, Shimadzu, Kyoto, Japan) to analyze N₂O and CO₂ concentrations, respectively. The instrument was calibrated monthly using pure N₂O and CO₂ standard gas. The flux of N₂O and CO₂ was calculated using the formula in Equation 1 (Wihardjaka et al., 2013):

$$E = (dC/dt) \times (V_{ch}/A_{ch}) \times (mW/mV) \times (273.2/273.2 + T) \dots\dots\dots(1)$$

where E is N₂O or CO₂ flux (mg m⁻² d⁻¹), dC/dt is increase rate of N₂O or CO₂ (mol ppb min⁻¹), V_{ch} is chamber volume (m³), A_{ch} is chamber area (m²), mW is molecular weight of N₂O or CO₂ (44.02 × 10³ mg mol⁻¹), mV is molar volume at 1 bar (22.41 × 10⁻³ m³ mol⁻¹), T is air temperature in inner chamber (°C)

All data were analyzed using ANOVA for a randomized complete block design. Treatment means were compared using the least significant difference (LSD) test at *p* < 0.05. The correlation between greenhouse gas emissions and soil chemical variables was carried out using Pearson correlation.

RESULTS AND DISCUSSION

Effect of manures and biochar-coated urea on plant height and biomass yield

Table 2 shows that only manure application significantly affected the agronomic parameter of plant height (*p* < 0.01), but it did not significantly affect sorghum biomass yield. The N input nor its interaction with manure application did not significantly affect plant height and sorghum biomass yield. The N input in the form of prilled urea and biochar-coated urea, either without or with microbial enrichment, did not significantly differ in sorghum growth parameters. Sorghum in rainfed land responded to manure application, where the plant height given cow manure or chicken manure was higher than without manure. It is possible that manure application improves soil structure and plant roots are freer to penetrate and explore to make nutrient uptake more effective. From Table 1, it can be seen that Typic Endoaquepts soil contains relatively high clay with low organic C content, meaning the soil has a high bulk density. Soils with high bulk density limit root growth by increasing soil strength and penetration resistance, which directly affects nutrient uptake and consequently plant yields (Yu et al., 2024).

Table 2. Plant height and yield of sorghum biomass affected by applying manure and N input in rainfed rice fields. The mean values followed by the same letter are not significantly different according to the Tukey test at $p \leq 0.05$. **Significant at $p < 0.01$, ^{ns}nonsignificant.

Treatment	Plant height cm	Dry biomass weight t ha ⁻¹
Manure application (A)		
A1: Without manure	122.2 ^a	38.68 ^a
A2: Cow manure	140.3 ^b	42.82 ^a
A3: Chicken manure	139.2 ^b	41.75 ^a
N input (P)		
P1: Farmers' fertilizer dose	139.2 ^a	44.44 ^a
P2: Prilled urea	129.8 ^a	39.12 ^a
P3: Biochar-coated urea	134.5 ^a	39.99 ^a
P4: Microbial-enriched biochar-coated urea	132.3 ^a	40.78 ^a
Group	0.575 ^{ns}	0.434 ^{ns}
Manure (A)	0.003 ^{**}	0.291 ^{ns}
Fertilizer (P)	0.904 ^{ns}	0.348 ^{ns}
A × P	0.764 ^{ns}	0.653 ^{ns}
CV, %	9.36	15.87

Effect of manures and biochar-coated urea on N₂O fluxes

The N₂O flux showed a dynamic trend, fluctuating sharply at the beginning of sorghum growth and tending to decrease as plants aged 45 to harvest, 125 d after germination (DAG) (Figure 2). The dynamics of N₂O flux were influenced by manure input. In plots without manure, the average N₂O flux was less than 1.5 mg m⁻² d⁻¹. The N₂O flux was lowest at 45 DAG, tending to increase at 95 and 125 DAG (Figure 2a). In the cow manure plots, N₂O flux was relatively high at the beginning of plant growth (15 and 25 DAG), especially those given prilled urea (P1 and P2) (Figure 2b). The N₂O flux did not differ significantly between treatments at 45, 95, and 125 DAG. In the chicken manure plots, the average N₂O flux was higher than 1.5 mg m⁻² d⁻¹ at 15 and 25 DAG, especially in treatments P1 and P4 (Figure 2c). Excessive urea application and microbial enrichment of biochar-coated urea appear to stimulate high N₂O fluxes in the early stages of sorghum growth. The N₂O fluxes from all urea fertilizer treatments in the chicken manure plots decreased as the sorghum aged from 45 DAG to harvest (125 DAG).

The combination of chicken manure (A3) and biochar-coated urea (P3) had a significant effect on reducing N₂O fluxes at the beginning, while cow manure (A2) and biochar-coated urea (P3) had a significant effect at 25 and 45 DAG. Even without manure application, P3 can reduce N₂O fluxes by 43.06% compared to the farmers' practices treatment. It is indicated that biochar-coated urea can be a potential means to reduce N₂O from soil.

The highest N₂O flux was generated by the combination of chicken manure (A3) and urea treatments (P1) during sorghum growth. When P4 treatment is combined with chicken manure (A3), N₂O flux is relatively high at the beginning of sorghum growth. It is expected that due to the high content of mineral N and C in chicken manure, it provides optimal conditions for denitrifying microbes to generate N₂O. Aligned with research from Alami et al. (2024), combining 70% of chemical N and 30% chicken manure emitted higher N₂O from soil, while 70% of chemical N and chicken manure combined with biochar N could reduce N₂O, amounting to 35.9%-65.7%. High N and C in chicken manure can promote the denitrification rate.

Plots without manure produced high N₂O flux due to the partial denitrification process, and the microbes involved were not efficient in utilizing the C available in the soil. Low C availability affects bacterial activity due to reduced energy intake and stimulates stress conditions, resulting in N₂O as the final product (Wan et al., 2023). Moreover, as the lack of C resource also results in a lack of energy source, particularly for denitrification bacteria, the denitrification process can be obstructed. The cow manure can reduce total N₂O emission, amounting to 16% compared to manure-free treatment. Compared to chicken manure, cow manure can decrease 34.14% of total N losses. It is thought to be due to slower decomposition. Therefore, cow manure is an eco-friendlier organic input than chicken manure despite its lower nutrient content.

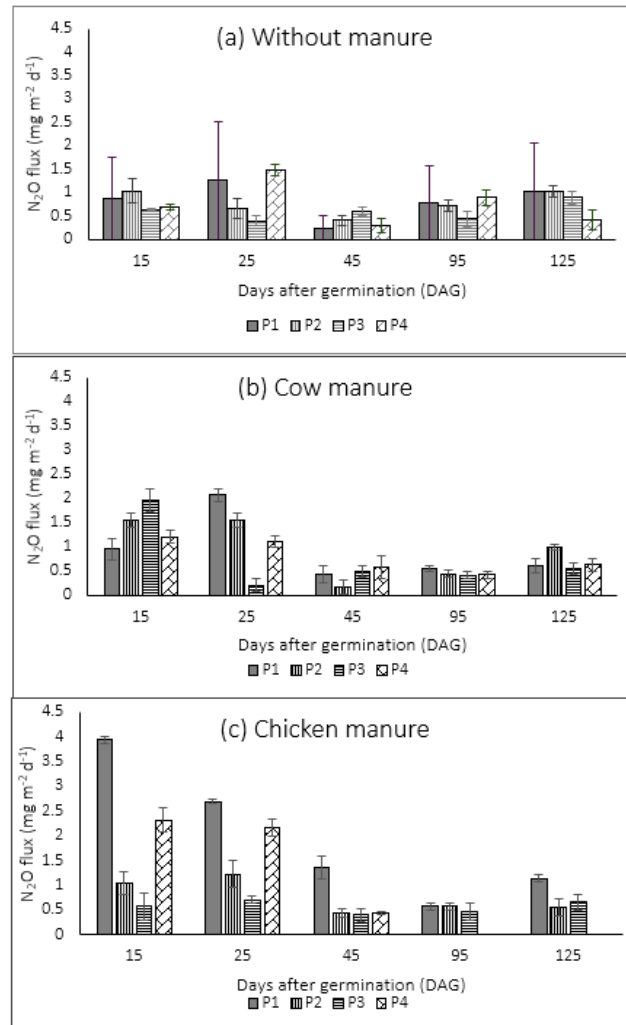


Figure 2. Nitrous oxide (N₂O) flux pattern due to fertilizer management in rainfed rice fields during sorghum growth. P1: Farmer's dose of fertilizer; P2: prilled urea; P3: biochar-coated urea; P4: microbial-enriched biochar-coated urea. Error bars are the standard deviation (SD).

Effect of manures and biochar-coated urea on CO₂ fluxes

The CO₂ fluxes in the urea and manure treatments fluctuated irregularly (Figure 3). Farmers' practical treatments resulted in high CO₂ fluxes when the sorghum was 45 DAG, especially in the plots with no manure and cow manure plots, but high CO₂ fluxes in the chicken manure plots at 15 DAG. The CO₂ fluxes were generally low at 125 DAG. In the plots without manure, biochar-coated urea with or without microbes generally produced relatively higher CO₂ fluxes than prilled urea, especially at 25 and 95 DAG (Figure 3a). In the cow manure plots, CO₂ fluxes from biochar-coated urea were generally lower than prilled urea and microbe-enriched biochar-coated urea throughout the sorghum growth phase (Figure 3b). In the chicken manure plots, biochar-coated urea was significantly lower than prilled urea and microbe-enriched biochar-coated urea, especially at 25 and 95 DAG (Figure 3c). At 15 DAG, cow manure can reduce by 21.61% and 6.02% of CO₂ fluxes compared to chicken manure and manure-free treatment, respectively. Moreover, cow manure can reduce around 38.18% and 27.27% of CO₂ fluxes compared to chicken manure and manure-free treatment at 95 DAG.

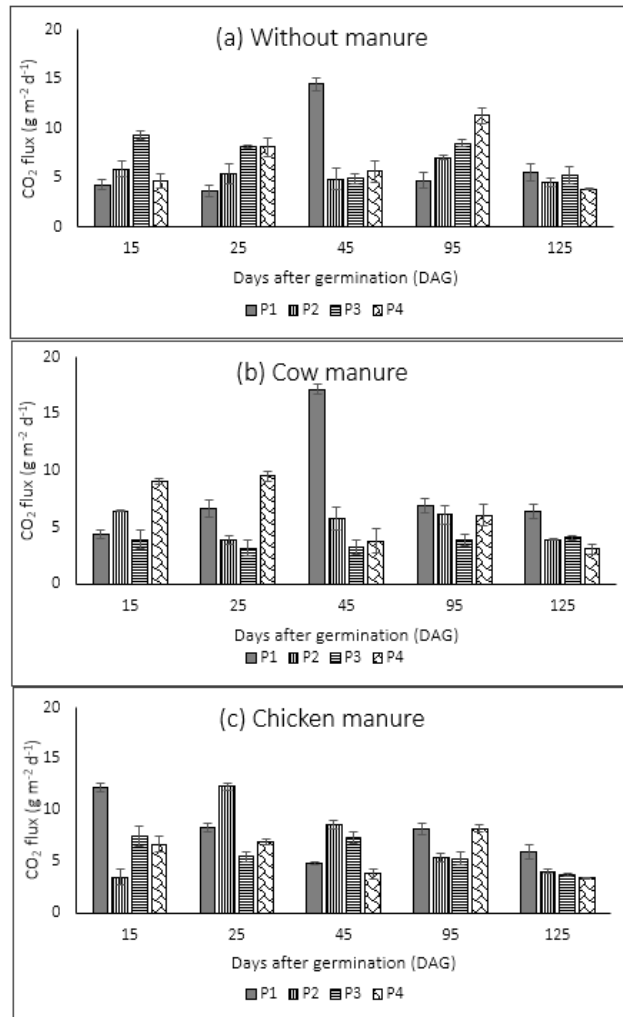


Figure 3. Carbon dioxide (CO₂) flux pattern due to fertilizer management in rainfed rice fields during sorghum growth. P1: Farmer's dose of fertilizer; P2: prilled urea; P3: biochar-coated urea; P4: microbial-enriched biochar-coated urea. Error bars are the standard deviation (SD).

These treatments did not have a significant effect on total CO₂. It might have been due to the stability of CO₂ fluxes in the short-term study. The CO₂ is related to soil C and is influenced by microbial respiration and soil C decomposition. It is different from N₂O, which is more sensitive to N transformation and is impacted by biochar and manure. A dynamic CO₂ flux in each plant phase was depicted in this study. Nevertheless, cow manure gave the lowest CO₂ flux compared to others at 15 and 95 DAG. It is expected that the organic content in cow manure is lower than that in chicken manure. Li et al. (2023) reported that the CO₂ emission rate was most affected by microorganism activities and high organic matter content, especially at the beginning of decomposition. In addition, the combination of N input and manure gave a significant effect on CO₂ flux at 125 DAG, with the lowest being A1P3 (2521 mg CO₂ m⁻² d⁻¹), followed by A1P4 and A2P3 (3998 and 4053 mg CO₂ m⁻² d⁻¹, respectively). It is indicated that biochar-coated urea itself and biochar-coated urea enriched with microbes can reduce CO₂ emission from soil in sorghum cultivation even without manure treatment.

N₂O and CO₂ emissions in rainfed fields

A glance at Table 3 depicts that there are significant effects from manure and N input on the N₂O emission. The N₂O emission in the plot without manure was 0.91 kg ha⁻¹, while the lowest was cow manure (0.85 kg ha⁻¹), so the application of cow manure can decrease the emission of N₂O as much as 7%. Mature manure application effectively reduces N loss in the form of N₂O in light-textured Inceptisol soils (Wihardjaka et al., 2025). The N input was significant on the N₂O emission. The lower N₂O emission was achieved significantly by P3 and P4 treatments, amounting to 0.72 and 0.77 kg ha⁻¹, respectively. The highest N₂O emission was achieved significantly by P1 treatment, around 1.21 kg ha⁻¹. Biochar-coated urea from corn biomass, either without or with microbial enrichment, can reduce N₂O emission by 20.8%-40.5% or 15.3%-36.4%, respectively, compared to the application of prilled urea to sorghum crops in rain-fed rice fields. On the contrary, the application of N input combined with manure did not show a significant effect on the CO₂ emission (Table 3).

Table 3. Total flux of N₂O and CO₂ after applying manure combined with N input. The mean values followed by the same letter are not significantly different according to the Tukey test at a $p < 0.05$ level of significance. *Significant at $p < 0.05$, ^{ns}nonsignificant.

Treatment	N ₂ O emission kg N ₂ O ha ⁻¹ season ⁻¹	CO ₂ emission kg CO ₂ ha ⁻¹ season ⁻¹
Manure application(A)		
A1: Without manure	0.91 ^{ab}	831 ^a
A2: Cow manure	0.85 ^b	736 ^a
A3: Chicken manure	0.96 ^a	821 ^a
N Input (P)		
P1: Farmers' fertilizer dose	1.21 ^a	947 ^a
P2: Prilled urea	0.91 ^{ab}	731 ^a
P3: Biochar-coated urea	0.72 ^b	698 ^a
P4: Microbial-enriched biochar-coated urea	0.77 ^b	784 ^a
Group	0.24 ^{ns}	0.751 ^{ns}
Manure (A)	0.02 [*]	0.249 ^{ns}
Fertilizer (P)	0.02 [*]	0.831 ^{ns}
A × P	0.07 ^{ns}	0.451 ^{ns}
CV, %	19.47	18.68

Pearson's correlation coefficients obtained indicate that soil N-total has a significant negative relationship with N₂O emission ($p < 0.05$), with a correlation coefficient of -0.46 (Table 4). Another prominent result was the cation exchange capacity (CEC) and pH relationship, with a correlation coefficient reaching -0.31. The relationship between N-total and N₂O emission is shown by the regression equation of $Y = 1.3342 - 1.2315X$; $R^2: 0.2357$, Y: N₂O emission, X: soil N-total. The result of regression analysis indicates that every 1 unit increase in N-total content will result in a 1.2315-unit decrease in N₂O emissions. This negative relationship indicates that the higher the total N content in the system, the lower the N₂O emissions tend to be. High total soil N is mostly in the form of stable N supported by a slow mineralization rate, so the reactive substrate (NH₄⁺ and NO₃⁻) available is low for the nitrification-denitrification process, which affects the low formation of N₂O. In addition, biochar can retain available N causing the N substrate for the denitrification process to be low. In the denitrification process, the availability of NO₃⁻ is low, resulting in low N₂O intermediate products (Wang et al., 2025).

Table 4. Correlation between plant growth, soil properties, and greenhouse gas emissions in one growing season. *Significant at $p < 0.05$. SOC: Soil organic C; CEC: cation exchange capacity.

Variable	pH	SOC	N-total	CEC	CO ₂ emission	N ₂ O emission
pH						
SOC	-0.16					
N-total	-0.02	-0.25				
CEC	-0.31	-0.09	0.15			
CO ₂ emission	-0.16	0.20	-0.22	0.09		
N ₂ O emission	0.08	-0.05	-0.46*	-0.26	0.05	

CONCLUSIONS

The dynamics of greenhouse gas fluxes during the growth phases of sorghum in rainfed rice fields appeared more regular for N₂O fluxes than for CO₂ fluxes. The N₂O flux pattern was relatively high at the beginning of the sorghum growth phase and tended to decrease during the generative growth phase of sorghum. Meanwhile, an irregular pattern was observed for CO₂ fluxes. The application of N input combined with manure had a significant effect on the N₂O emission, but not on the CO₂ emission in sorghum cultivated in rainfed rice fields. Biochar-coated urea can reduce N₂O flux more than conventional fertilizer dosage. Biochar-coated urea from corn biomass, either without or with microbial enrichment, can reduce N₂O emission by 20.8%-40.5% or 15.3%-36.4%, respectively, compared to the application of urea prilled to sorghum crops in rainfed rice fields. Of the several soil chemical variables, only total N was significantly negatively correlated with N₂O emission in rainfed rice fields planted with sorghum. These results identified that biochar-coated urea can support integrated fertility strategies and reduce environmental impact. Further research should focus on optimizing microbial formulations and evaluating long-term effects across different conditions.

Author contribution

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

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