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RESEARCH

Effect of organic amendment and biochar-coated urea on sorghum yield, nitrogen use efficiency, and soil water infiltration in rainfed lowland

Anicetus Wihardjaka[1], Nourma Al Viandari[1], Terry Ayu Adriany[1], Hidayatuz Zu'amah[2], Elisabeth Srihayu Harsanti[2*], Agus Supriyo[1], Etty Pratiwi[1], I Gusti Made Subiksa[1], Wahida Annisa Yusuf[3], and Cahyoadi Bowo[4]

[1]Indonesian Research Center for Food Crops, National Research and Innovation Agency, Cibinong Science 8 Center, Jl. Raya Jakarta-Bogor, Cibinong, West Java 16915, Indonesia.
[2]Indonesian Research Center for Horticulture, National Research and Innovation Agency, Cibinong Science Center, Jl. Raya Jakarta-Bogor, Cibinong, West Java 16915, Indonesia.
[3]Directorate of Land Protection and Provision, Directorate General of Agricultural Land and Irrigation, Ministry of Agriculture, Jakarta, Indonesia.
[4]Agricultural Faculty of Jember University, Jember, East Java, Indonesia.
[*]Corresponding author (esharsanti@gmail.com).
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ABSTRACT

Sorghum (*Sorghum bicolor* (L.) Moench) is one of the food crops that has the potential to be developed on rainfed lowlands and is also adaptive to the impacts of climate change. Improving fertilizer quality and providing organic ameliorants is one solution to increase sorghum productivity and nutrient availability. Urea fertilizer is commonly used; however, it is not efficiently utilized by plants. Corn biomass can be used as bio-charcoal (biochar) to improve N fertilizers' efficiency while mitigating nitrous oxide (N_2O) emissions. This research aims to determine the effect of urea fertilizer (urea prill, biochar-coated urea, and microbial-enriched biochar-coated urea) and organic ameliorants (cow and chicken manure) on sorghum yields, N uptake, and soil water infiltration on rainfed lowland. The research was designed with randomized blocks, three replicates, and factorial treatment consisting of three urea fertilizer treatments and three organic ameliorant treatments. The parameters measured included sorghum yields, flux of N_2O, N uptake, N use efficiency (NUE), and soil water infiltration. The interaction between organic ameliorant and the application of biochar-coated urea significantly affected the grain and biomass yield of sorghum, NUE, but not significantly affected N uptake. Sorghum yields increased by 12.5%-20.7% in the application of biochar-coated urea enriched with consortia microbes accompanied by the organic ameliorant. The use of biochar-coated urea enriched with consortia microbes was more effective in plots applied organic ameliorant, both cow and chicken manure, namely significantly increasing the grain and biomass yield of sorghum, NUE, and water infiltration rate, and significantly reducing N_2O emissions and the global warming potential index.

Key words: Nitrous oxide, nitrogen use efficiency, organic ameliorant, *Sorghum bicolor*, sorghum yield, urea coated biochar.

INTRODUCTION

Indonesia has dry land with an area of 122 million hectares (Mulyani et al., 2014), of which 3.3 million hectares is rainfed lowland (Mulyani et al., 2022). The main obstacles to rainfed land are low soil fertility and vulnerability to drought stress. With only three wet months and an average annual rainfall of less than 1500 mm, rainfed lowland is an agroecosystem that often experiences drought stress as one of the impacts of climate change (Wihardjaka et al., 2020a).

The productivity of crops, especially food crops, on rainfed land is relatively low due to not being utilized optimally and low soil fertility, accompanied by several limiting factors. On one hand, food crop productivity ranges from 3.0-3.5 t ha^{-1} for lowland 'Ciherang' rice (Wihardjaka et al., 2020b), 4-5 t ha^{-1} for shelled 'Lamuru' corn (Lalu and Syuryawati, 2017; Seran et al., 2023). Rainfed land in the dry season can be used for cultivating food crops, adaptive and drought-tolerant plant species such as sorghum.

Sorghum (*Sorghum bicolor* (L.) Moench), a versatile cereal plant that can grow on dry land, land with low soil fertility, and is tolerant to drought stress. Sorghum has the potential to be developed on idle land, abandoned land, or sub-optimal land which is currently still not widely used (Ostmeyer et al., 2022; Kurniasari et al., 2023; Elsiddig et al., 2023). Indonesia has only 4355 ha used for extensive sorghum cultivation, while rainfed areas have not been optimally utilized (Statistics Indonesia, 2021). As a food crop, sorghum seeds have the potential to replace rice and corn which are hampered by the reduction in planting area due to land conversion to non-agriculture. Apart from that, sorghum can be used as human food, animal feed, organic fertilizer, and bio-fuel (Elsiddig et al., 2023). Sorghum flour can replace 15%-50% of wheat flour (Irawan and Sutrisna, 2011). Compared to rice and corn, farmers are less interested in cultivating sorghum intensively (Kurniasari et al., 2023). The world average dry grain productivity of sorghum is 1.41 t ha^{-1}, where the highest is 3.71 t ha^{-1} in America and the lowest is 1.00 t ha^{-1} in Africa, while in Asia it is 1.11 t ha^{-1} (Kurniasari et al., 2023). In Indonesia, national sorghum productivity per year gains 2-3 t ha^{-1} meanwhile global sorghum productivity means 2.7 t ha^{-1}. However, national sorghum productivity is usually lower compared to other Asian countries, which is caused by several factors including a lack of focus on developing sorghum agriculture, a lack of understanding of the benefits and potential of this crop, and climate and soil conditions that do not always support optimal growth.

Better sorghum growth still requires support from production facilities such as good quality seeds, high-yielding varieties, nutrient input from inorganic and organic fertilizers, and water availability. Organic input can be sourced from animal waste, which apart from being a nutrient supplier, also plays a role in enhancing soil properties (Wang et al., 2020; Githongo et al., 2023). In the long term, organic materials loosen the soil, improve water-holding capacity, strengthen aggregates, and increase infiltration capacity and soil porosity (Rayne and Aula, 2020; Fu et al., 2022). Providing organic fertilizer can increase the efficiency of using inorganic fertilizer. The combination of compost with synthetic chemical fertilizers can increase rice yields by 4.7% (Al Viandari et al., 2022). The input of inorganic N fertilizer that is widely used by cereal farmers is urea fertilizer.

Globally, the need and use of N fertilizer is always increasing to meet the demand for food, feed, and fiber (Awada and Phillips, 2021). Amounting to 120 million tons of N fertilizer are applied annually, it represents close by 60% of all NPK fertilizer input (Valenzuela, 2024). Intensive cultivation of food crops (rice and corn) requires nutrient input from inorganic N fertilizer. The N fertilization on sorghum plants is generally not carried out intensively. Nitrogen is a crucial macronutrient in generating of amino acids, proteins, and pigments, e.g., chlorophyll in plants (Ostmeyer et al., 2022; Elsiddig et al., 2023; Valenzuela, 2024). Nitrogen constitutes 1% to 5% of total DM (Muratore et al., 2021). Ammonium (NH_4^+) and nitrate (NO_3^-) are dominant forms which are absorbed by plants (Zayed et al., 2023). The motion of these forms is affected by mass flow; therefore, diffusion plays a crucial role to these forms (Saengwilai et al., 2021). The existence of NO_3^- is abundant form compared to NH_4^+ in aerobic soils, where the former and the latter concentrations typically range 1 to 5 mM and 20 and 200 µM. On one hand, NO_3^- is leached easily, on the other hand, NH_4^+ is released slowly as its strongly adsorbed by soil particles (Muratore et al., 2021).

The use of urea fertilizer [$CO(NH_2)_2$] on food crops is generally not used efficiently by plants (Lawrence et al., 2021). Nitrogen use efficiency (NUE) is low due to N forms in urea can rapidly be emitted to the surroundings (Ransom et al., 2020). It is because around 50%-55% N loss throughout nitrification-denitrification, ammonia volatilization, surface runoff, and leaching along with poor N uptake by plants (Lawrence et al., 2021; Ostmeyer et al., 2022; Govindasamy et al., 2023). Therefore, enhancing N obtain in soil is required to stimulate crop growth and yield coupled with conserving environmental condition (Saengwilai et al., 2021).

Excessive use of N fertilizer has negative impacts on the environment, including nitrate leaching and global warming emission, particularly nitrous oxide (N_2O) (Govindasamy et al., 2023; Valenzuela, 2024). The N_2O is a greenhouse gas from the agricultural sector which has a global warming potential of 310 times compared to

CO_2 as an absorber of infrared radiation (Awada and Phillips, 2021). Nitrous oxide has lifetime of 116 ± 9 yr in the stratosphere (Müller, 2021). Future anthropogenic N_2O-N emissions are estimated to reach around 9.7 Tg N_2O-N yr^{-1} in 2050 which is amounting to 46% of total global N_2O-N emissions in 2050 (Aryal et al., 2022). Efforts to streamline the use of N fertilizer can be made in various ways/methods, including urea coating.

Coating materials can be inorganic materials and organic polymers (Lawrencia et al., 2021). As a urea coating, biochar from biomass waste is a prospective material that is cheap, easy to obtain, and available in abundance around food crop cultivation areas. Biochar is a product resulting from pyrolysis at 250-300 °C. Biochar is useful as a soil conditioner, as well as C sequestration, enhanced water, N, and P retention, grain yield improvement, surface and groundwater quality, also reduced greenhouse gases emissions (Guenet et al., 2021; Button et al., 2022; Xia et al., 2022). The N nutrient released slowly by fertilizer coated with biochar will be utilized efficiently by plants.

Additionally, the amount of N absorbed by plants depends on the adequacy of water moisture in the soil. Therefore, limitation of N availability in drought-affected soils significantly decreases crop production (Ostmeyer et al., 2022). In rainfed drought-prone farming systems, efficiently using applied N fertilizers is a key challenge in addressing N deficiencies in crops like sorghum (Elsiddig et al., 2023). The N uptake of sorghum in dry land in Indonesia is still limited to research. To meet the challenges of increasing sorghum yield whereas mitigating climate change impacts, a strategy is required to enhance N use efficiency (NUE). Therefore, the aim of this study was to observe sorghum yield, NUE and soil infiltration rate of Vertic Endoaquepts treated with organic ameliorant and biochar-coated urea in rainfed lowlands.

MATERIALS AND METHODS

Experimental site and design

The field experiment was performed in rainfed rice fields in Pati district (6°46'33" S, 111°11'44" E), Central Java province, during 2023-2024 rainy season. The experimental location has Vertic Endoaquepts soil type with clay loam texture (35% sand, 44% silt, 21% clay), slightly acidic soil reaction (pH-H_2O 5.54), low organic C content (0.31% organic C), low total N (0.41% N), moderate cation exchange capacity (17.09 cmol kg^{-1}) with exchangeable cations K, Na, Ca, Mg 0.04, 0.09, 8.83, 0.25 cmol kg^{-1}, respectively, available P (140.9 mg P kg^{-1}), and available K (103.6 mg K kg^{-1}).

The experiment was arranged in complete randomized blocks design, replicated three times, with factorial treatments, namely first factor in the form of organic ameliorant (O1 = without livestock manure, O2 = cow manure, O3 = chicken manure) and the second factor in the form of urea-based N fertilizer (N1 = urea prill, N2 = biochar-coated urea, N3 = microbial-enriched biochar-coated urea). The organic ameliorant dosage was 2 t ha^{-1} dry weight, while the urea dosage was 92 kg N ha^{-1}. Biochar was made through pyrolysis process from corn biomass raw material at 250-300 °C. Biochar from corn (*Zea mays* L.) biomass used contained 0.91% N, 0.21% P, 1.92% K, and pH 10.5. The ratio of biochar and urea prill was 1:4. Microbial consortia consisting of three strains of bacteria (*Bacillus aryabhattai*, *Bacillus aerius*, *Bacillus marisflavi*) were used to enrich biochar (size 50 mesh) urea coating.

Cultural practices

The land was prepared by tillage and continued with the creation of experimental unit plots. Two seedlings of sorghum (*Sorghum bicolor* (L.) Moench) were transplanted from the nursery after 21 d after growing in each plot measuring 5 m × 4 m. Sorghum seedlings were planted with a spacing of 60 cm × 30 cm on 20 September 2023. In this experiment, sorghum 'Samurai' was used. Organic ameliorants according to the treatment were given together with soil processing by immersion.

The dose of organic ameliorant was 2 t ha^{-1}. In this experiment, cow manure used contained 21.7% C-organic, 0.75% N, 9.6 mg P kg^{-1}, 9.7 mg K kg^{-1}, while chicken manure contained 22.9% C-organic, 0.92% N, 21.4 mg P kg^{-1}, 2.8 mg K kg^{-1}. Nitrogen fertilizer was given according to the treatment, namely 200 kg ha^{-1} urea. The P fertilizer was given all at once 7 d after planting. The K fertilizer was given in stages, namely ½ dose 7 d after planting and the next ½ dose 30 d after planting. All fertilizers were given in the ditch hole next to the main crop. Maintenance was carried out intensively, both pest and disease control and weed control.

Data collection and analysis

The variables observed included seed and biomass yield, plant height, N uptake, N use efficiency (NUE), N loss in the form of N_2O, and soil water infiltration rate. Plant height was measured randomly from 10 plant samples per plot. Seed and biomass yields were measured from 2 m × 2 m tiles per plot. Biomass samples were taken as a composite for each plot and analyzed for total N content to calculate N uptake. According to Singh et al. (2023), N concentrations (Nc) were provided in percentage, and the values of total aboveground N uptake were calculated by Equation 1. Nitrogen use efficiency was calculated by Equation 2:

$$\text{Nitrogen uptake (kg N ha}^{-1}\text{)} = \text{Dry biomass (kg ha}^{-1}\text{)} \times \text{Nc} \quad (1)$$

$$\text{Nitrogen use efficiency (NUE)} = \text{N uptake (kg N ha}^{-1}\text{)/N input of fertilizer (kg N ha}^{-1}\text{)} \quad (2)$$

Gas samples were taken from each plot using the closed chamber method at the third critical growth phase of sorghum. The chamber size is 20 cm width × 40 cm length × 30 cm height, where at the top of the chamber there is an injection hole and a thermometer placement hole. Simultaneously with gas sampling, the temperature in the chamber was recorded. Gas samples were analyzed for N_2O concentration using gas chromatography equipped with an electron capture detector (ECD). The N_2O flux was calculated using the Kang et al. (2021) with Equation 3:

$$E = \rho \times [V/A] \times [\Delta c/\Delta t] \times [273/(273+T)] \quad (3)$$

where E is N_2O flux, ρ is N_2O density, V is the volume of the chamber (m^3), A is the area of the chamber (m^2), Δc/Δt is an average increase of gas concentration, and T is mean temperature in the chamber (°C). The global warming potential of N_2O is calculated by multiplying the N_2O flux by 310 CO_2 equivalents.

Undisturbed soil samples were taken with ring samples at the topsoil layer's depth (0-15 cm) for water infiltration rate analysis, which refers to Atmanto (2017) and Army and Tsabitah (2023).

The data were tested for normal distribution and homogeneity of variance before further statistical analysis. Statistical analyses of all data were performed using the Minitab program ver. 19 (Minitab, State College, Pennsylvania, USA). Differences between means were tested with a one-way ANOVA. When significant effects ($p < 0.05$) were found, Tukey's honest significant difference (HSD) test was used to compare mean values.

RESULTS AND DISCUSSION

Rice growth and grain yield

Low soil fertility in rainfed agroecology has an impact on suboptimal crop productivity, including sorghum. The N fertilizer is an essential element in sorghum production; it results in a significant rise in crop yield (Ma et al., 2019). Improvement of N nutrient availability is carried out by improving N availability from urea fertilizer and the use of organic ameliorants. Table 1 shows data that is normally distributed for all variables with p-value > 0.05. As seen in Table 1, the provision of organic ameliorants and the provision of biochar-coated urea each significantly affected sorghum yields ($p < 0.01$), although the interaction between the two factors was not significantly different ($p > 0.05$). The highest sorghum yield was significantly shown in the application of organic ameliorants from chicken manure followed by cow manure, increasing by 17.4% and 17.0% respectively compared to the treatment without manure. Providing rich sources of organic N fertilizer or manure can be combined with synthetic N applications that improve cereal yield and NUE by the use of controlled release urea (CRU) (Wang et al., 2023). Applying manure into the fertilizing strategy can improve soil properties by enhancing soil nutrient availability, therefore it improves crop yields (Ferreira et al., 2022). The treatment of urea coated with biochar enriched with consortia microbes significantly gave higher sorghum yields than the treatment of urea coated with biochar and prilled urea treatments, with average dry yields of 9.81, 9.15, 8.13 t ha^{-1}, respectively (Table 1). The application of urea coated with biochar enriched with consortia microbes together with the use of organic ameliorants increased sorghum grain yields by 12.5%-20.7% in rainfed lowland. The beneficial agronomic impact of nutrient-enriched biochar from organic coatings that develop within its pores, enhancing its nutrient retention capacity (Acharya et al., 2023).

The application of biochar-coated urea did not significantly affect the biomass yield of sorghum, but the organic ameliorant treatment and its interaction with biochar-coated urea significantly affected, each with $p < 0.01$ (Table 1). The application of organic ameliorant from cow manure produced the highest dry biomass of sorghum followed by the chicken manure treatment, each producing an average of 3.63 and 1.59 t ha^{-1} higher than the treatment without manure. The biomass weight of the cow manure treatment was higher than that of chicken manure. Manure input in farming systems may be an effective management practice to decrease the excessive synthetic N input while providing crop yields of grain and biomass (Ren et al., 2023).

Table 1 shows that the application of organic ameliorant and biochar-coated urea significantly affected N uptake, at $p < 0.01$ and $p < 0.05$ respectively, while the interaction of the two treatment factors was not significantly different ($p > 0.05$). The N uptake in the provision of cow manure ameliorant was significantly higher than the chicken manure treatment, increasing by 13.2% and 11.2% respectively compared to without manure.

Table 1. Grain yield, N uptake, efficiency of N uptake on applying organic ameliorant and urea fertilizers in sorghum cropping. The means in the same column followed by the same letter do not differ significantly according to the Tukey test at the 0.05 level. **Significant at $p < 0.01$, *significant at $p < 0.05$, ^{ns}nonsignificant at $p > 0.05$.

Manure (O)	N fertilizer (N)	Grain yield	Biomass weight	N uptake	N use efficiency
		t ha^{-1}	t ha^{-1}	kg N ha^{-1}	kg N kg^{-1} N
Without manure	Urea pril	6.82^{c}	38.11^{cd}	291^{a}	6.46^{c}
	Biochar-coated urea	8.16^{bc}	37.56^{cd}	321^{a}	7.14^{b}
	Microbial-enriched biochar-coated urea	9.33^{ab}	39.01^{a-d}	294^{a}	6.53^{c}
Cow manure	Urea pril	9.06^{ab}	42.80^{abc}	325^{a}	7.23^{ab}
	Biochar-coated urea	9.87^{b}	43.89^{ab}	363^{a}	8.08^{a}
	Microbial-enriched biochar-coated urea	9.51^{ab}	38.88^{a-d}	339^{a}	7.53^{ab}
Chicken manure	Urea pril	8.52^{bc}	36.44^{d}	307^{a}	6.82^{c}
	Biochar-coated urea	9.42^{ab}	38.51^{bcd}	341^{a}	7.59^{ab}
	Microbial-enriched biochar-coated urea	10.59^{a}	44.47^{a}	359^{a}	7.98^{a}
p-value	Manure (O)	**	**	**	*
	N fertilizer (N)	**	ns	*	**
	O × N	ns	**	ns	**

The N uptake in the application of biochar-coated urea either without or enriched with consortia microbes significantly increased, where the increase in biochar-coated urea was higher than in the treatment of biochar-coated urea + consortia microbes, increasing by 8.9% and 7.5% respectively compared to without manure (Table 1). Biochar can increase the capacity of plant roots to access N nutrients in the soil. In addition, biochar increases the abundance of N-fixing bacteria on its surface and increases the N bioavailability (Rasse et al., 2022). The urea fertilizer is coated with proper material to convert it to slow-release fertilizer (SRF), which mainly controls the release rate of nutrients into the soil by decreasing the solubility of the fertilizer (Priya et al., 2024). Nitrogen is released slowly from biochar-coated urea fertilizer. The release of N from the rhizosphere is utilized by sorghum as needed during its growth, where effective N uptake plays a role in the formation of carbohydrates and proteins (Li et al., 2024). The N release synchronizes better with plant N uptake, the effects of which vary with soil and weather conditions, cultivation regimes, CRU, and organic fertilizer types (Wang et al., 2023).

The N use efficiency (NUE) of N fertilizer was significant in the N fertilizer factor treatment, organic ameliorant factor treatment, and the interaction of the two factors, each with a significant value of $p < 0.01$. The provision of organic ameliorant significantly increased NUE compared to without manure, which increased by 13.4% (cow manure treatment) and 11.2% (chicken manure treatment). In all organic ameliorant treatments, urea prill gave a lower NUE value than the biochar-coated urea treatment, either without or enriched with microbes. Biochar-coated urea, either without or enriched with microbes, increased the average NUE value by 11.1% and 7.3%, respectively (Table 1). The provision of biochar-coated urea, either without or enriched with consortia microbes, increased the NUE by 6.3%-13.2% and 15.3%-22.2%, respectively, in plots that were also given organic ameliorant. This means that organic ameliorant encourages plants to utilize N efficiently from N fertilizer applied to the soil. Increase in NUE with biochar as coating urea is largely attributed to a putative slow-release effect that biochar matrices have on N fertilizers (Rasse et al., 2022).

Sorghum yield is influenced by the amount of N absorbed and effective for sorghum plant growth. The N absorption at a certain limit can actually reduce sorghum yield as shown by the relationship between N uptake and sorghum grain yield with the equation $Y = -7\times10^{-5}x^2 + 0.068x - 5.413$, $R^2 = 0.278$, Y: sorghum grain yield, x: N uptake (Figure 1). Nitrogen as the main component of chlorophyll plays an important role in the process of photosynthesis (Elsiddig et al., 2023). Increasing N uptake allows sorghum to produce better biomass and photosynthate production. Optimal N uptake can also increase the efficiency of water and other nutrient use, so that plants can survive unfavorable environmental conditions (Li et al., 2024).

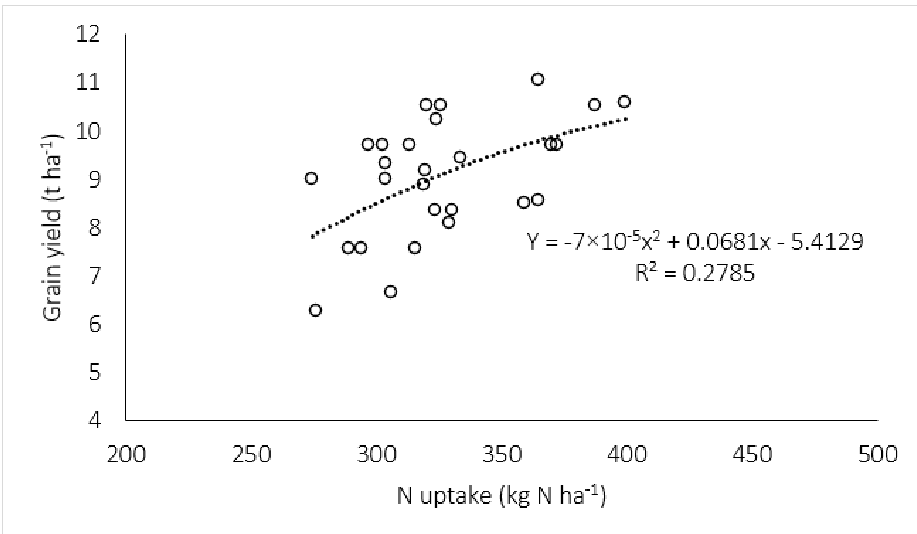

Figure 1. Relationship between N uptake and sorghum grain yield in rainfed lowland, rainy season of 2023-2024.

Flux of nitrous oxide

Table 2 also shows data that is normally distributed for all variables with p-value > 0.05. The biochar-coated urea treatment did not significantly affect N_2O emissions, N loss, and the global warming potential (GWP) index, while the provision of organic ameliorants and their interaction with biochar-coated urea significantly ($p < 0.01$) on the three observed parameters (Table 2). The N_2O emissions in the biochar-coated urea + consortia microbe treatment was significantly lower than the biochar-coated urea treatment, while the highest N_2O emissions were significantly in the treatment without manure. Biochar-induced reductions in N_2O losses can result from a higher proportion of NO_3^- being converted to N_2 and N_2O during microbial processes of nitrification-denitrification in soil (Rasse et al., 2022). The application of biochar also plays a role in reducing N losses in addition to increasing C content in the soil (Acharya et al., 2023).

The average N_2O emissions in the treatments of chicken manure, cow manure, and without ameliorant were 0.74, 0.83, 0.87 kg N_2O ha^{-1} $season^{-1}$, respectively (Table 2). Organic ameliorants reduced N_2O emissions by an average of 10.8% (cow manure) and 14.9% (chicken manure). Similarly, N loss showed that the lowest and highest N losses were shown in the chicken manure and no-manure treatments, respectively. Compared to the treatment without organic ameliorant, N losses from chicken manure and cow manure decreased by 16.1% and 4.8%, respectively (Table 2). Nitrogen from chicken manure is more soluble, quickly released, and easily washed out compared to N from cow manure. Modification of urea fertilizer by coating with biochar slows down the release of N into the soil solution, which means that the fertilizer is slow to decompose, and prevents large amounts of N loss and leaching (Acharya et al., 2023; Banik et al., 2023).

Table 2. Nitrous oxide (N_2O) emission on applying organic ameliorant and urea fertilizers in sorghum cropping. The means in the same column followed by the same letter do not differ significantly according to the Tukey test at the 0.05 level. GWP: Global warming potential; CO_2-e: CO_2 equivalent **significant at $p < 0.01$, *significant at $p < 0.05$, ^{ns}nonsignificant at $p > 0.05$.

Manure (O)	N fertilizer (N)	N_2O emission	% N loss	GWP
		kg N_2O ha^{-1} season^{-1}	%	kg CO_2-e ha^{-1} season^{-1}
Without manure	Urea prill	0.90^{ab}	0.64^{ab}	278^{b}
	Biochar-coated urea	0.74^{bc}	0.52^{ab}	229^{bc}
	Microbial-enriched biochar-coated urea	0.98^{a}	0.71^{a}	304^{a}
Cow manure	Urea prill	0.76^{bc}	0.54^{ab}	236^{bc}
	Biochar-coated urea	0.93^{ab}	0.66^{ab}	287^{b}
	Microbial-enriched biochar-coated urea	0.80^{abc}	0.57^{ab}	248^{bc}
Chicken manure	Urea prill	0.83^{abc}	0.58^{ab}	256^{bc}
	Biochar-coated urea	0.67^{c}	0.47^{b}	207^{c}
	Microbial-enriched biochar-coated urea	0.72^{bc}	0.51^{ab}	223^{bc}
p-value	Manure (O)	**	*	**
	N fertilizer (N)	ns	ns	ns
	O × N	**	*	**

Loss of N in the form of N_2O can reduce sorghum yields. As seen in Figure 2, a negative relationship is shown by sorghum grain yield and N_2O flux with a linear equation Y = -0.807x + 9.689 (Y: sorghum grain yield, x: N_2O flux). Applying excessive N does not greatly enhance crop yields, instead, it reduces NUE and leads to severe environmental issues due to the N losses in the form of N_2O and NO_3^- (Ma et al., 2019).

In addition, the provision of organic ameliorants and urea coating with biochar either without or enriched with microbes is one of the efforts to mitigate greenhouse gas emissions, especially N_2O, which also improves sorghum plant productivity and soil quality.

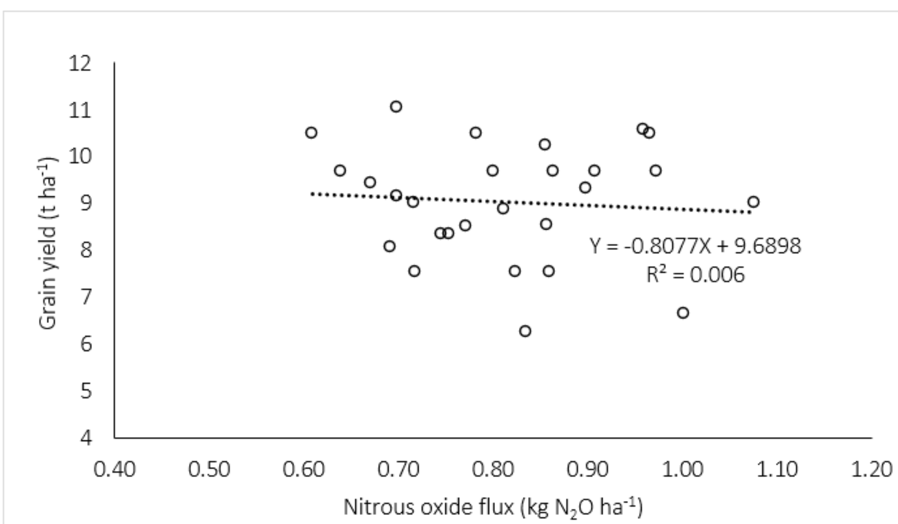

Figure 2. Relationship between flux of nitrous oxide and sorghum grain yield in rainfed lowland, 2023-2024 rainy season.

The average GWP index in the treatments of chicken manure, cow manure, and without ameliorant were 22, 257, 270 kg CO_2-equivalente ha^{-1} $season^{-1}$, respectively. Compared to without organic ameliorant, the chicken manure and cow manure treatments significantly reduced the GWP index by 15.6% and 4.8%, respectively. This means that the provision of organic ameliorant from chicken manure effectively reduces N_2O emissions, N loss, and global warming potential from rainfed dry land planted with sorghum. The provision of organic ameliorant and improvement of NUE through urea coating with biochar can be seen as efforts to mitigate greenhouse gas emissions, especially N_2O from the food crop subsector, which is in line with national efforts to reduce anthropogenic greenhouse gas emissions in the agricultural sector.

Soil water infiltration

As seen in Figure 3, one of the physical properties of the soil that is significantly affected by the N fertilization treatment, ameliorant application, and the interaction between the two is the soil infiltration rate, with each p-value < 0.01. In the organic ameliorant treatment plot, the application of biochar-coated urea either with or without microbial consortium enrichment significantly increased the soil infiltration capacity. The combination of organic ameliorant with biochar-coated urea significantly increased the infiltration rate by 72%-100% (without microbial enrichment) and 100%-158% (with microbial enrichment). This means that the use of biochar as a urea coating is effective in improving Inceptisol soil infiltration in sorghum plantations. The combination of organic material with biochar was found to be very effective in improving some physical properties of the soils such as soil water holding capacity (WHC), soil water infiltration, soil water availability, nutrient retention, soil hydraulic conductivity, and soil aeration (Chang et al., 2021). The increase in soil infiltration rate due to the provision of organic ameliorants and biochar helps sorghum plants to access nutrients, especially N, effectively.

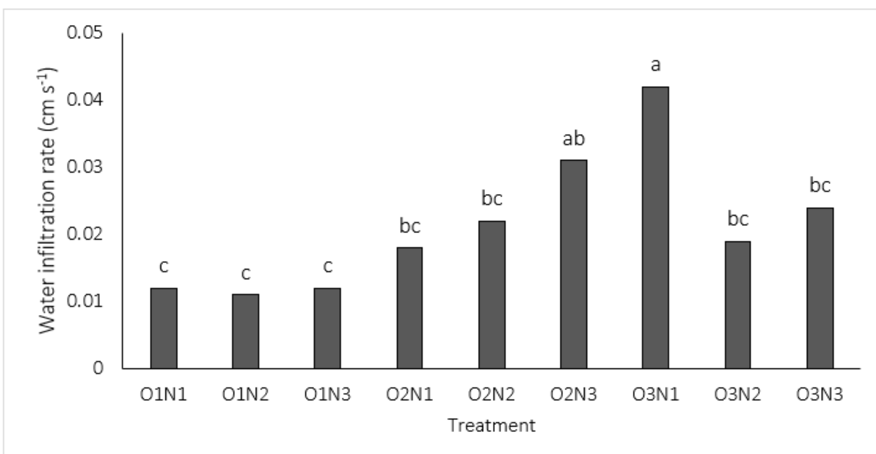

Figure 3. Soil water infiltration on applying organic ameliorant and urea fertilizers in sorghum cropping. O1: Without organic ameliorant; O2: cow manure; O3: chicken manure; N1: urea prill; N2: biochar-coated urea; N3: microbial-enriched biochar-coated urea. The bars followed by the same letter do not differ significantly according to the Tukey test at the 0.05 level.

The combination of organic ameliorants and biochar increases the soil water infiltration capacity, which is beneficial for the sorghum plant root system and nutrient uptake, especially N. Zhang et al. (2023) reported that the incorporation of wheat straw biomass also increased the soil water infiltration capacity and N availability in the soil. The primary factors affecting the average infiltration rate include soil bulk density, moisture content, total porosity, capillary porosity, and soil aggregation (Zhang et al., 2023). Plant roots have more freedom to explore and reach essential nutrients, and prevent excessive leaching of nutrients (Kulmatiski et al., 2017). Increased soil water infiltration capacity supports better root growth and N nutrient uptake efficiency (Zhang et al., 2023).

CONCLUSIONS

Improvement of urea fertilizer through biochar coating ensures that N is available slowly and reduces N loss in the form of nitrous oxide (N_2O). The enrichment of consortia microbes in biochar-coated urea has a dual function in addition to increasing the N use efficiency (NUE), it also stimulates the growth and yield of sorghum to be better. The interaction between organic ameliorant and the application of biochar-coated urea significantly affects the yield of sorghum seeds and biomass, NUE, but not significantly on N uptake. The use of biochar-coated urea enriched with consortia microbes is more effective in plots given organic ameliorant, both cow manure and chicken manure, namely significantly increasing the yield of sorghum seeds and biomass, NUE, and water infiltration rate in soil, and significantly reducing N_2O emissions and the global warming potential index. Sorghum yields increased significantly by 12.5%-20.7% in the application of biochar-coated urea enriched with consortia microbes accompanied by the application of organic ameliorant. The provision of biochar-coated urea, either without or enriched with consortia microbes, increased significantly the NUE by 6.3%-13.2% and 15.3%-22.2%, especially when combined with the provision of organic ameliorant. Application of both factors can increase the rate of groundwater infiltration by up to 100%, and when enriched with consortia microbes can increase it by up to 18% in rainfed lowland. The combination of organic ameliorants and biochar-coated urea has the potential to increase NUE, improve sorghum productivity, and at the same time act as an effort to adapt to and mitigate climate change in rainfed lowland.

Author contributions

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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