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Original Article

Bioenergy sorghum production on degraded tropical grasslands: Implications for marginal land utilization

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Abstract

The feasibility of sorghum [*Sorghum bicolor* (L.) Moench] production as a renewable energy feedstock was evaluated through multi-cycle field trials on degraded tropical grasslands dominated by *Imperata cylindrica* in Indonesia. The study aimed to quantify the achievable yield levels and soil responses under different nitrogen (N) fertilizer rates, combined with or without compost and a microbial inoculant, at two contrasting sites representing moderately fertile and nutrient-poor soils. Nitrogen was confirmed to affect biomass production, grain yield, stem juice sugar content, and plant N content, whereas compost and the microbial inoculant had only limited effects. Maximum biomass yields reached 25–32 t ha^{-1} per cycle (50–64 t ha^{-1} $year^{-1}$ with two annual crops), sufficient to meet the life-cycle assessment threshold for net greenhouse gas reduction through coal co-firing in power generation. In contrast, yields at the nutrient-poor site remained lower (16–24 t ha^{-1} per cycle). Successive sorghum cultivation decreased soil organic carbon, cation exchange capacity, and soil pH, although compost application mitigated these declines. These field results provide empirical benchmarks for evaluating the performance of sorghum-based energy systems on marginal tropical lands. They can support techno-economic and environmental modeling of low-carbon energy scenarios.

Keywords: Marginal land, Bioenergy, Feedstock, Nitrogen fertilizer, Sorghum

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Introduction

Global energy demand has increased, driven by population growth and economic development. The demand is expected to rise further, with projections indicating a 6% increase by 2030 compared with 2024 levels (IEA, 2024). In the long term, continued reliance on fossil fuels is unrealistic, as their availability is depleting. (El-Araby, 2024; Malode et al., 2021). A reduction in carbon dioxide emissions is necessary to mitigate climate change. Thus, there is an urgent need to develop and utilize alternative renewable energy sources (Shuaibu et al., 2024; El-Araby, 2024; Mahapatra et al., 2021; Morrow, 2021; Suprapto, 2024). Major renewable energy sources include solar, wind, geothermal, hydropower, and bioenergy. As of 2022, renewable energy accounted for 12.9 % of global final energy consumption (REN21, 2025), with bioenergy contributing nearly two-thirds of this share. In electricity generation specifically, the contribution of bioenergy is generally lower than that of solar and wind. However, it remains an essential component of renewable energy, due to its characteristics such as stability independent of weather conditions; usability for multiple formats, including heat, electricity, and liquid fuel; and suitability as a local energy supply in rural areas. Therefore, further expansion of the use of bioenergy is expected, but the challenge lies in securing the biomass resources as raw materials. Substantial concerns have been raised regarding the competition between biomass use and food production, as well as the risk of deforestation associated with woody biomass. Instead, several possible feedstocks, including agricultural residues, crops grown on marginal lands, or crops with very high yields, have been recommended as more sustainable options.

Marginal land refers to areas where environmental or socioeconomic constraints limit agricultural productivity, making them generally unsuitable for high-yield food crop production. The marginal land has increasingly been considered a potential resource for bioenergy crop production (Edrisi et al., 2022; Yu et al., 2024). A major example of such marginal land in the tropics is the *Imperata cylindrica* (alang-alang)-dominated grasslands, which often emerge as secondary vegetation following deforestation. The alang-alang leaves become highly flammable during the dry season and often cause wildfires, which interrupt vegetative succession and prevent forest regeneration, while alang-alang itself survives the fire with its underground rhizomes. The lands would be thus persistently covered by the grass, not delivering effective ecosystem services (Central Bureau of Statistics, 2017). The alang-alang grassland has been reported to cover 35 million hectares in Southeast Asia (Garrity et al., 1996), including approximately 24.2 million ha in Indonesia (Central Bureau of Statistics, 2017). Utilizing such alang-alang-covered degraded grasslands for the cultivation of biomass crops would be an effective option to increase the production of biomass energy feedstock.

Sorghum [*Sorghum bicolor* (L.) Moench] is one of the most promising crops for this purpose. It is a tropical C_4 photosynthetic plant that can produce biomass efficiently, reaching up to 42 t ha^{-1} per cultivation under appropriate conditions (Tang et al., 2018). Furthermore, it is tolerant to abiotic stresses such as salinity and drought (Fracasso et al., 2016; Pasini et al., 2014; Sadia et al., 2019), making it compatible with cultivation on lands that are unfavorable for food crops such as rice or maize. As an energy feedstock crop, sorghum has the advantage of being available in multiple formats. Sorghum lignocellulose can be processed into solid fuels, such as bio pellets and biochar, for thermal applications and electricity generation (Bennett and Anex, 2009; Zegada-Lizarazu and Monti, 2012). In addition, grains and stem juice from certain sorghum varieties can be used to produce ethanol and other fermentation-derived products. The process residue, bagasse, may also be used for fermentation. Thus, sorghum is one of the most promising candidates for cultivating biomass crops on the currently unused grassland mentioned above. However, for sorghum cultivation on currently underutilized grasslands to be a viable approach for sustainable energy production, good sorghum yields in such systems are mandatory. Yield per unit area has been one of the critical factors considered in the life cycle assessment of the effectiveness of sorghum bio pellets as a way to cut net greenhouse gas emissions (Wiloso et al., 2020). One potential problem with sorghum production in degraded grasslands is that such lands often have low soil fertility and inadequate water supply, and, hence, may not be productive enough to give acceptable biomass yields. The yield per unit area can be improved by applying enough fertilizer. However, excessive use of fertilizers should be avoided, as it can cause various problems such as salinity, soil acidification, loss of soil microbial diversity, and nitrous oxide emission as a strong greenhouse gas.

While many previous reports have focused on the potential biomass production of sorghum under favorable growing conditions or in semi-arid regions, empirical data remain scarce regarding its productivity in highly constrained tropical marginal lands, where the actual cultivation of energy crops is expected to play an important role. Therefore, this study examined whether sorghum can achieve biomass yields compatible with life-cycle assessment (LCA)-based thresholds under constrained tropical grassland conditions. By doing so, this work addresses an important gap between field agronomy and bioenergy sustainability assessment, a perspective that has received limited attention in the existing literature. We hypothesized that sorghum could attain such yields under practical N fertilization levels. To evaluate this hypothesis, we conducted multi-year field experiments at two locations in Indonesia, converting highly degraded *Imperata*-dominated grasslands to sorghum cultivation. Unlike studies based primarily on regional simulations or short-term trials, this study provides multi-year field evidence to assess the feasibility of integrating sorghum-based bioenergy systems into low-carbon energy scenarios under humid tropical conditions.

Material and Methods

Site description

Field experiments were conducted at two sites with contrasting environments: Cibinong-Bogor of West Java Province (site CB; 6°29'18" S, 106°51'21" E) and Katingan of Central Kalimantan (site K; 1°53'21" S, 113°27'51" E). The two sites differed in soil type, soil nitrogen content, precipitation, and solar radiation (Supplementary Tables S1 and S2). Soil type was classified as Alfisols at site CB and Entisols at site K. Weather data during the experimental period were obtained from nearby meteorological stations.

Both sites were at low elevations above sea level (150 m at site CB and 50 m at site K) and had high relative air humidity (82.5 % in site CB and 81.7 % in site K) (Supplementary Table S1). According to the Schmidt-Ferguson classification, the climate at site CB was categorized as tropical very wet, whereas that at site K was tropical wet. Site CB was characterized by stable high temperature (~26–27 °C), abundant year-round rainfall (~2,600–3,000 mm), and minimal seasonal dryness. In contrast, site K also had high annual precipitation and warm temperatures, but some months were relatively drier.

Soils at site CB were silt-dominated, whereas those at site K were loamy sand. The total soil N was low at both sites. Available P was low at site CB, while available K was low at site K (Supplementary Table S2). The C/N ratio was higher at site CB, and the soils at both sites were moderately acidic (Supplementary Table S2).

Experimental design and operation

A single sorghum variety was used in each site; var. Super 1 at site CB and var. Super 2 at site K. Both sorghum varieties are widely cultivated in Indonesia as sweet sorghum, known for their high biomass production. The experiment was conducted in 2016–2018 at site CB and 2017–2018 at site K. At site CB, each plot was 5 × 5 m, with 4 m between plots across all treatments and replicates. Two seeds per hole were sown at 0.75 m intervals in the north-south direction, with a row spacing of 0.25 m. At site K, sorghum was cultivated using the same practice as at site CB, with the exception that each plot measured 4 × 4 m and three seeds were sown per hole. All trials followed good agricultural practices, and the main agronomic practices and growth periods are summarized in Supplementary Table S3. Nitrogen fertilizer was applied at five levels: 0 (N1), 25% (N2), 50% (N3), 75% (N4), and 100% (N5) of the level recommended conventionally, which is 300 kg urea ha^{-1} (138 kg N ha^{-1}) (Kansas State University, 2013; Vanderlip, 1993). Compost was not applied (C–) or applied at 20,000 kg ha^{-1} (C+), and a microbial inoculant was not applied (M–) or applied at 500 kg ha^{-1} (M+). All plots were applied with phosphorus as triple superphosphate at 67.5 kg P_2O_5 ha^{-1} and potassium as potassium chloride at 75 kg K_2O ha^{-1}. The three treatment combinations were arranged in a completely randomized block design (CRBD) with three replications, yielding 60 plots. The same five N and two microbial inoculant levels were tested at site K, but compost was applied to all plots to improve the unfavorable soil texture. Each combination of the two treatments was replicated three times and arranged in a CRBD with 30 plots in total. Irrigation was applied at both sites when there was no rainfall for several days, especially during the plant's early growth period. The shoot was harvested manually.

Microbial inoculant

The application of inoculants is carried out by mixing 200 g of *Azospirillum brasilense*, 100 g of *Pseudomonas fluorescens*, and 3 kg of vesicular-

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arbuscular mycorrhiza (VAM) with 500 kg of compost ha^{-1}, which functions as a carbon source, protects the microbes from extreme conditions, and serves as a medium for even distribution to the root zone during soil tillage. Synergy among microbes was expected through the fixation of N_2 into NH_4^+ by *Azospirillum*, the solubilization of bound phosphate into $H_2PO_4^-$ by *Pseudomonas*, and the expansion of nutrient absorption through VAM hyphae. For seed treatment, sorghum seeds were coated with the inoculant using a 10% sugar solution as an adhesive and initial energy source, soaked for 30 minutes, and then dried to ensure microbial colonization around young roots during germination. The critical maintenance phase for 2–4 weeks' post-application involves avoiding excessive phosphate fertilizers (to keep VAM active), delaying the use of chemical pesticides (replaced with the biopesticide Beauveria bassiana), and monitoring for N/P deficiency symptoms, which are addressed with liquid organic fertilizers or re-inoculation.

Plant and soil analyses

At harvest, three plants were randomly selected from each plot to measure dry weight biomass (DWB), total grain weight (TGW), and stem juice sugar content (SC), and the mean of the three plants was used as the plot value. DWB was determined per plant after drying to constant weight in a universal oven (Memmert UN 450); TGW was measured per plant using a digital scale; and SC was assessed from juice extracted from the middle stem using a digital refractometer (ATAGO Ltd.). Nitrogen contents in sorghum plants and soils were analyzed using the Kjeldahl method. Soil physical and chemical properties were determined from samples collected at depths of 0–30 cm. Baseline properties before cultivation are presented in Supplementary Table S2, and post-cultivation analyses were conducted in 2016–2018 at site CB and in 2017–2018 at site K.

Statistical analysis

Data were analyzed using a general linear model (GLM) with R software (version 4.5.0) (R Core Team, 2023). Data from each cultivation cycle were analyzed separately to evaluate treatment effects under the specific environmental conditions of each season. For the data from Site CB, a three-way factorial Analysis of Variance (ANOVA) was performed to evaluate the effects of compost (C), microbial inoculant (M), N level (N), and their interactions on DWB, TGW, SC, and plant N content in plant analyses, and on organic C, total N, cation exchange capacity (CEC), and pH (H_2O) in soil analyses. For Site K, a two-way factorial ANOVA was conducted to test the effects of M and N, with nitrogen levels treated as categorical factors. All factors were considered fixed effects. Type II sums of squares were calculated using the Anova function in the 'car' package (Fox and Weisberg, 2019). Normality of residuals was assessed using the Shapiro–Wilk test and Q–Q plots, and homogeneity of variance was evaluated using Levene's test. Slight deviations from normality were observed for several combinations of site, cycle, and parameter (e.g., DWB in cycle 1 at site CB; Supplementary Fig. S1). Log transformation did not substantially improve the residual distribution. No evidence of heterogeneity of variance was detected in any model. Therefore, given the robustness of ANOVA and the experiment's balanced design, analyses were performed on the original scale. When interaction terms or main effects were significant, pairwise comparisons of estimated marginal means were performed using the 'emmeans' package (Lenth and Plaskowski, 2025) with Tukey adjustment for multiple comparisons. Effect sizes were evaluated using partial eta squared (η^2). All statistical significance levels were set at $p < 0.05$.

Results

Environmental conditions

During sorghum cultivation, the average daily rainfall at site CB was 18.56, 17.03, and 17.06 mm for cycles 1, 2, and 3, respectively, whereas at site K it was 13.75 and 9.04 mm for cycles 1 and 2 (Supplementary Table S3).

Soils at site CB were generally fertile with relatively high base saturation, and thus, reasonable crop yields were expected under proper management. In contrast, soils at site K, derived from sandy parent material, were less fertile and required careful management for agricultural use. We characterized how biomass production and plant N uptake responded to increasing N fertilizer rates, and how these responses were modified by soil amendments, including compost and microbial inoculants.

Effect of nitrogen fertilizer and soil amendments on plant growth

Sorghum cultivation trials on unused grasslands began in 2016 at both sites. At site K, however, growth in 2016 was highly uneven, likely due to soil conditions;

thus, data from that year were excluded. At site CB, a second ratoon harvest was attempted but failed due to disease pressure during the rainy season. Accordingly, only dry-season results are reported: 2016–2018 for site CB and 2017–2018 for site K. We evaluated plant performance based on DWB, TGW, and SC, while plant N content was additionally assessed as an indicator of N uptake and nutritional status. The values obtained in each cycle at both sites are summarized in Supplementary Tables S4–S7. The effects of the treatments were evaluated using analysis of variance (ANOVA) (Table 1).

Biomass yield

At site CB, the mean DWB across treatments was 213.7, 209.9, and 183.1 g plant^{-1} in cycles 1, 2, and 3, respectively. In cycle 1, DWB showed a significant M × N interaction and a significant main effect of N (Table 1). No significant effects involving C were detected. In cycle 2, neither main nor interaction effects were significant. In cycle 3, a significant C × M interaction was detected (Table 1), while no significant effects involving N were detected.

Table-1. Summary of ANOVA for plant production parameters.

Site	Cycle	Term [1]	df [2]	DWB			TGW			SC			N content		
				F	p-value	η^2	F	p-value	η^2	F	p-value	η^2	F	p-value	η^2
CB	1	C	1	0.9	0.348	0.02	0.5	0.465	0.01	0.1	0.802	0.00	2.0	0.161	0.05
		M	1	1.2	0.283	0.03	0.0	0.860	0.00	0.1	0.795	0.00	0.0	0.971	0.00
		N	4	8.4	0.000 **	0.46	6.3	0.000 **	0.39	0.6	0.633	0.06	7.9	0.000 **	0.44
		C:M	1	0.3	0.559	0.01	0.3	0.587	0.01	0.3	0.614	0.01	0.1	0.786	0.00
		C:N	4	2.3	0.071	0.19	3.2	0.022 *	0.24	0.8	0.528	0.08	6.9	0.000 **	0.41
		M:N	4	2.7	0.042 *	0.22	2.2	0.092	0.18	0.3	0.872	0.03	0.6	0.663	0.06
		C:M:N	4	2.6	0.054	0.20	1.5	0.232	0.13	0.9	0.501	0.08	3.7	0.012 *	0.27
	2	C	1	0.1	0.713	0.00	1.5	0.233	0.04	0.4	0.554	0.01	0.7	0.420	0.02
		M	1	0.2	0.655	0.01	0.0	0.870	0.00	0.1	0.747	0.00	16.1	0.000 **	0.29
		N	4	1.7	0.161	0.15	1.4	0.246	0.12	3.6	0.013 *	0.27	1.4	0.255	0.12
		C:M	1	0.9	0.347	0.02	0.5	0.490	0.01	0.0	0.827	0.00	2.4	0.133	0.06
		C:N	4	1.0	0.432	0.09	0.5	0.740	0.05	4.1	0.007 **	0.29	0.2	0.920	0.02
		M:N	4	0.3	0.846	0.03	0.6	0.658	0.06	0.9	0.484	0.08	4.0	0.008 **	0.29
		C:M:N	4	0.2	0.910	0.02	0.3	0.887	0.03	0.3	0.869	0.03	0.2	0.923	0.02
	3	C	1	0.6	0.451	0.01	2.2	0.145	0.05	0.7	0.412	0.02	0.8	0.391	0.02
		M	1	0.3	0.599	0.01	0.0	0.909	0.00	0.7	0.421	0.02	0.2	0.651	0.01
		N	4	1.4	0.239	0.13	0.6	0.697	0.05	1.3	0.285	0.12	3.0	0.029 *	0.23
		C:M	1	5.1	0.029 *	0.11	0.2	0.628	0.01	0.0	0.879	0.00	1.2	0.274	0.03
		C:N	4	0.7	0.613	0.06	1.2	0.336	0.11	2.3	0.077	0.19	0.7	0.605	0.06
		M:N	4	1.3	0.270	0.12	0.8	0.553	0.07	0.8	0.528	0.08	0.7	0.626	0.06
		C:M:N	4	1.5	0.233	0.13	1.2	0.324	0.11	2.5	0.060	0.20	0.9	0.502	0.08
K	1	M	1	7.7	0.012 *	0.28	12.2	0.002 **	0.38	0.1	0.755	0.01	6.9	0.016 *	0.26
		N	4	1.9	0.156	0.27	5.4	0.004 **	0.52	1.3	0.321	0.20	2.0	0.140	0.28
		M:N	4	1.5	0.229	0.24	1.7	0.199	0.25	0.1	0.973	0.02	0.6	0.638	0.11
	2	M	1	0.0	0.854	0.00	0.3	0.595	0.01	0.3	0.598	0.01	4.0	0.059	0.17
		N	4	3.2	0.036 *	0.39	8.3	0.000 **	0.63	1.5	0.240	0.23	3.1	0.040 *	0.38
		M:N	4	2.3	0.098	0.31	1.2	0.348	0.19	1.0	0.418	0.17	4.4	0.010 *	0.47

[1] C: compost, M: microbial inoculant, N: N dosage

[2] degree of freedom

* Significant effect at $p < 0.05$ level; ** Significant effect at $p < 0.01$ level

We then examined how these effects were expressed across treatments. In Site CB, interactions involving N were significant in multiple cycle–parameter combinations. Because our primary focus was to evaluate yield responses to N fertilizer rates, we visualized the data in Site CB in two ways: as treatment means across combinations of C and N (Figure 1), and across combinations of M and N (Figure 2). These complementary visualizations summarize treatment means at each N level in the presence or absence of compost or microbial inoculants. The C × M interaction, although statistically significant in cycle 3 (Table 1), was associated with only a small effect and did not yield significant pairwise differences in the post-hoc Tukey-adjusted pairwise comparisons (Supplementary Figure S2); therefore, it was not included in the main visualization. In cycle 1, DWB at N1 was lower than

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at N4 and N5 under M– conditions, whereas the differences were not detected under M+ conditions (Figure 2). This contrast indicates that the magnitude of the DWB response to N application rates depended on the presence of microbial inoculation, consistent with the presence of the M × N interaction observed in this cycle.

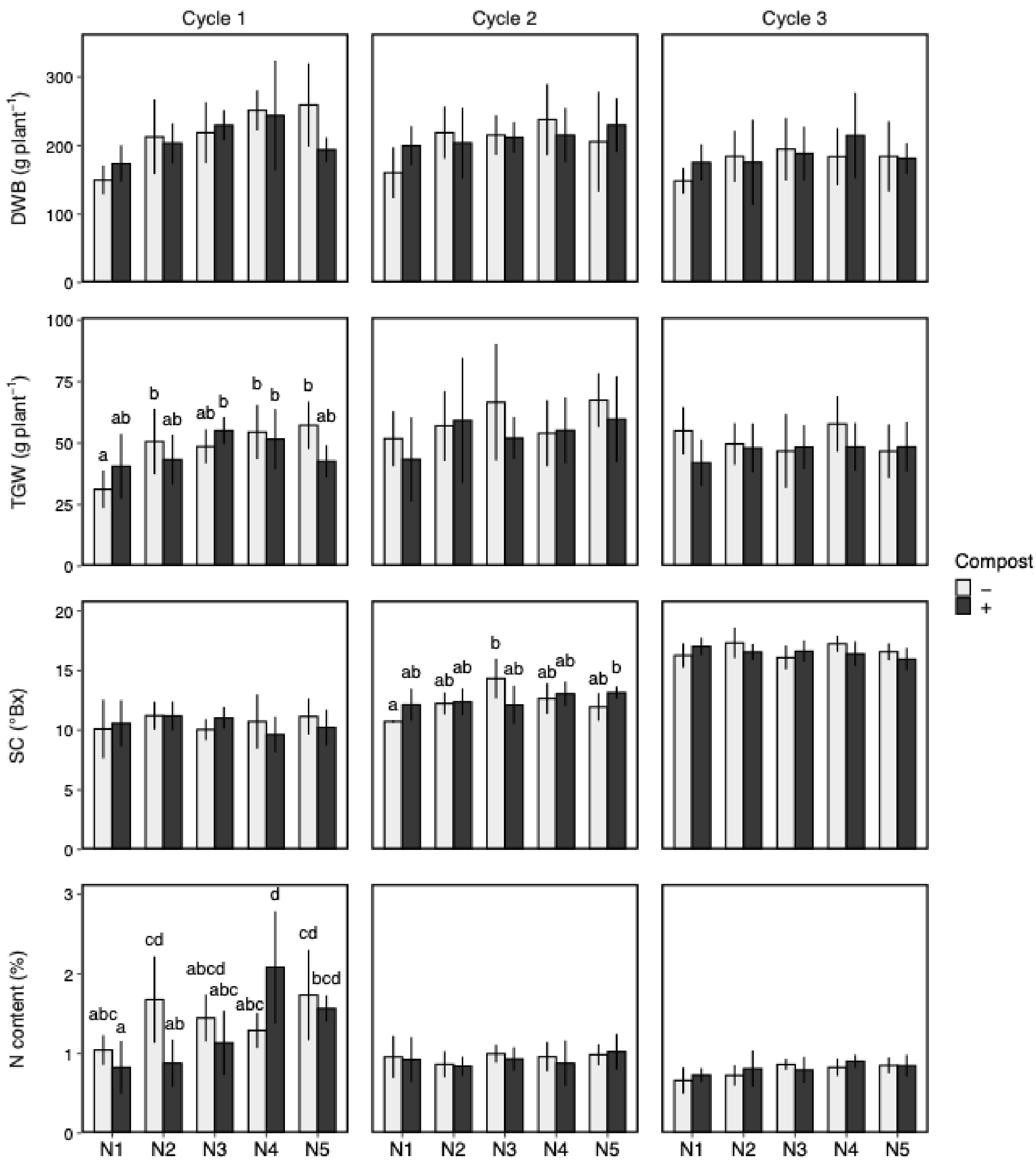

Figure-1. Plant production at site CB (C × N, collapsed over M).
Bars show observed means (n = 6) with standard deviations for the 10 treatment groups defined by the combinations of C and N. Post-hoc pairwise comparisons with Tukey adjustment were performed only for cycle–parameter combinations in which the C × N interaction was significant in the ANOVA (Table 1). Different letters indicate significant differences among the C × N treatment groups within each cycle ($p < 0.05$), based on estimated marginal means from a three-way ANOVA including C, M, and N as factors.

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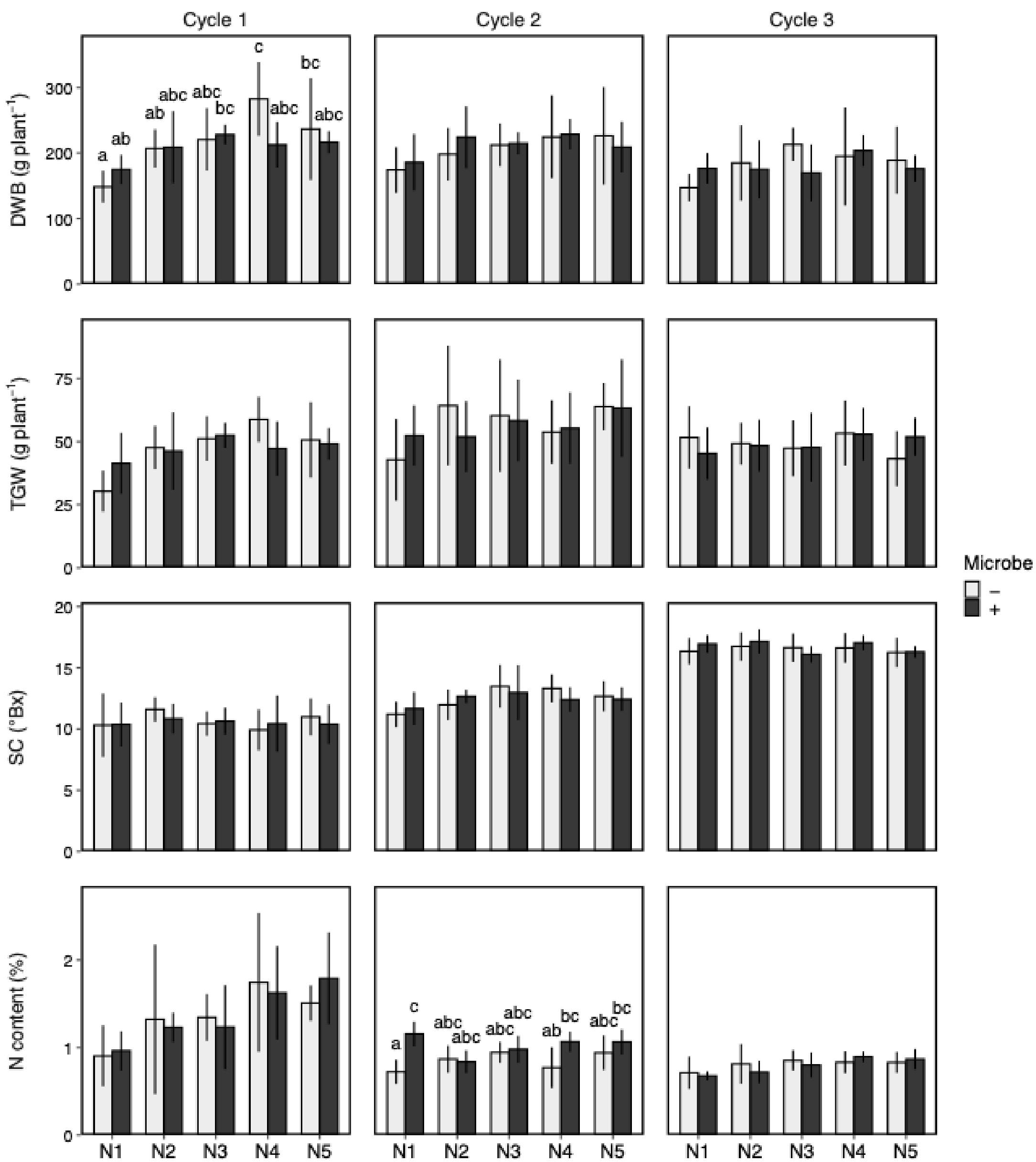

Figure-2. Plant production at site CB (M × N, collapsed over C).
Bars show observed means (n = 6) with standard deviations for the 10 treatment groups defined by the combinations of M and N. Post-hoc pairwise comparisons with Tukey adjustment were performed only for cycle–parameter combinations in which the M × N interaction was significant in the ANOVA (Table 1). Different letters indicate significant differences among the M × N treatment groups within each cycle ($p < 0.05$), based on estimated marginal means from a three-way ANOVA including C, M, and N as factors.

At site K, the mean DWB across treatments was 150.7 g plant^{-1} in cycle 1 and 99.7 g plant^{-1} in cycle 2. The two-way ANOVA, with M and N as factors, revealed significant main effects of M in cycle 1 and of N in cycle 2, but no significant M × N interaction in either cycle (Table 1). We therefore visualized the data for this site in two figures, showing the main effect of M (Figure 3) and N (Figure 4) separately. Post-hoc pairwise comparison with Tukey adjustment showed that mean DWB under M+ conditions were higher than under M– conditions in cycle 1 (Figure 3), consistent with the significant main effect of M (Table 1). Meanwhile, the post-hoc pairwise comparisons with Tukey adjustment did not identify significant pairwise differences among N levels in cycle 2 (Figure 4), despite the significant main effect of N detected by ANOVA (Table 1). This discrepancy may reflect the conservative nature of the Tukey adjustment, particularly in the presence of relatively large within-treatment variability. Nevertheless, the overall trend in mean DWB across N levels (Figure 4) was consistent with the direction suggested by the significant main effect of N in the ANOVA (Table 1).

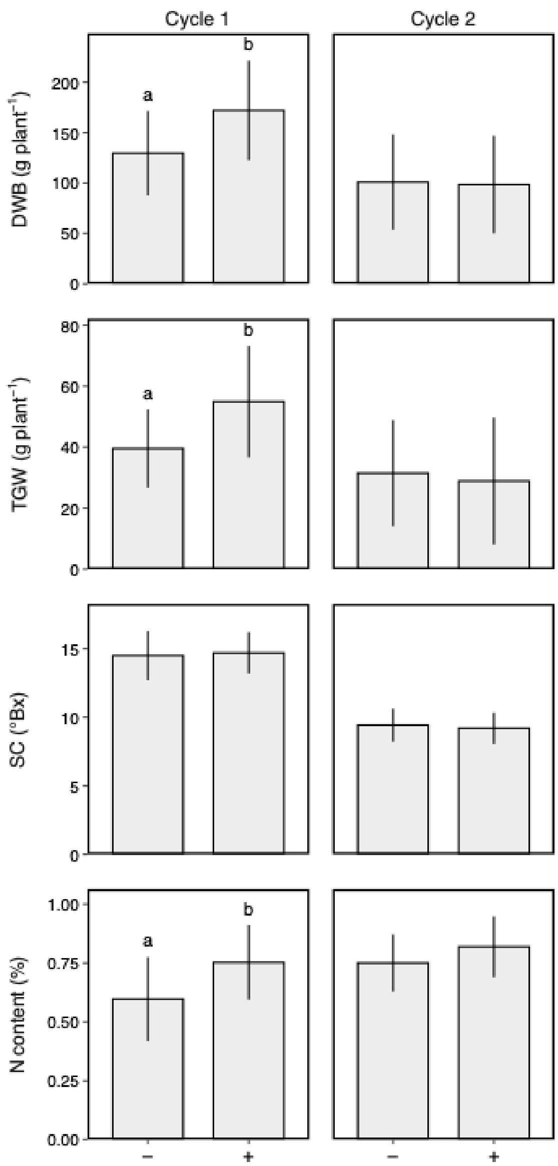

Figure-3. Plant production at site K (main effect of M).
Bars show observed means (n = 15) with standard deviations for the two treatment groups defined by the presence (+) or absence (–) of microbial inoculation. Post-hoc pairwise comparisons with Tukey adjustment were performed only for cycle–parameter combinations in which the main effect of M was significant and was not qualified by a significant M × N interaction in the ANOVA (Table 1). Different letters indicate significant differences between M– and M+ within each cycle ($p < 0.05$), based on estimated marginal means from a two-way ANOVA including M and N as factors.

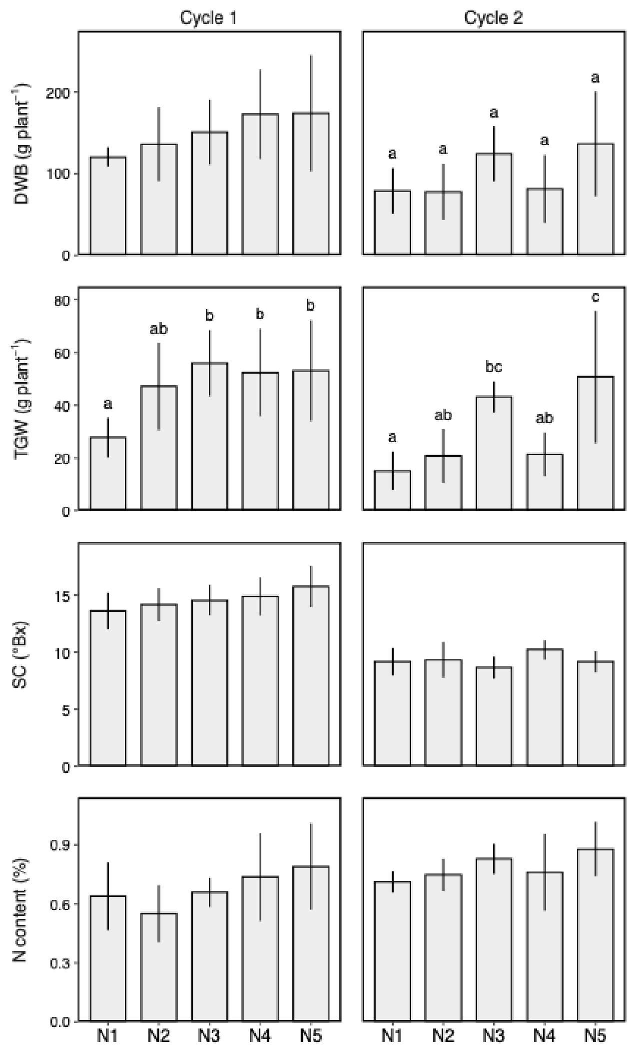

Figure-4. Plant production at site K (main effect of N).
Bars show observed means (n = 6) with standard deviations for the five treatment groups defined by N level. Post-hoc pairwise comparisons with Tukey adjustment were performed only for cycle–parameter combinations in which the main effect of N was significant and was not qualified by a significant M × N interaction in the ANOVA (Table 1). Different letters indicate significant differences among N levels within each cycle ($p < 0.05$), based on estimated marginal means from a two-way ANOVA including M and N as factors.

Grain yield

At site CB, the mean TGW across treatments was 47.5, 56.6, and 49.1 g plant^{-1} in cycles 1, 2, and 3, respectively. Significant effects of treatment factors on TGW were observed only in cycle 1, with a significant main effect of N and a significant C × N interaction (Table 1), whereas no significant effects involving M were observed. In cycles 2 and 3, neither main nor interaction effects were significant (Table 1). Treatment means of TGW for C × N and M × N combinations are shown in Figures 1 and 2. In cycle 1, mean TGW under C– conditions was larger at higher N levels, as observed in the difference between the values at N1 and N4 or N5 (Figure 1). Meanwhile, such pairwise differences were not evident under C+ conditions, which is consistent with the significant C × N interaction indicating that the response to N depended on compost application (Table 1). Consistent with the ANOVA results, no clear treatment-dependent patterns were evident in cycles 2 or 3 (Figures 1 and 2).

At site K, the mean TGW across treatments was 47.3 and 30.2 g plant^{-1} in cycles 1 and 2, respectively. Significant main effects of M and N were detected in

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cycle 1, and a significant main effect of N was detected in cycle 2 (Table 1). Post-hoc pairwise comparisons with Tukey adjustment showed significantly higher TGW under M+ conditions than under M– conditions in cycle 1 (Figure 3), whereas TGW was significantly higher at higher N supply in both cycles (Figure 4). These results are consistent with the significant main effects of M and N detected by ANOVA (Table 1).

Stem juice sugar content

At site CB, the mean SC across treatments was 10.6, 12.5, and 16.6°Bx in cycles 1, 2, and 3, respectively. In cycles 1 and 3, no significant main effects or interactions of treatment factors were detected (Table 1). In cycle 2, a significant main effect of N and a significant C × N interaction were detected, whereas no significant effects involving M were observed (Table 1). Treatment means across C × N and M × N combinations are shown in Figures 1 and 2. In cycle 2, SC at N3 was higher than that at N1 under C– conditions. Meanwhile, such a difference was not observed under C+ conditions (Figure 1), consistent with the significant C × N interaction (Table 1). However, the difference in SC depending on N levels and compost application was not consistently observed across cycles (Figure 1).

At site K, the mean SC across treatments was 14.6 and 9.3°Bx in cycles 1 and 2, respectively. In both cycles, neither significant main effects of M or N, nor a significant M × N interaction, were detected (Table 1). Mean SC values remained relatively constant across M and N treatments (Figures 3 and 4).

Plant nitrogen content

At site CB, the mean plant N content across treatments was 1.4, 0.93, and 0.80% in cycles 1, 2, and 3, respectively. In cycle 1, significant effects of N, C × N, and C × M × N were detected (Table 1). In cycle 2, a significant main effect of M and a significant M × N interaction were detected, while no significant effects involving C were detected. In cycle 3, only the main effect of N was significant. Treatment means for the C × N and M × N combinations are shown in Figs. 1 and 2 for all three cycles. In addition, the significant C × M × N interaction in cycle 1 and the significant main effect of N in cycle 3 are separately illustrated by the corresponding treatment means in Supplementary Figures S3 and S4, respectively. In cycle 1, mean plant N content increased with N level under C+ conditions (Figure 1). Meanwhile, although the N content at N4 or N5 was numerically higher than that at N1 under C– conditions, they were not statistically different (Figure 1), consistent with the significant C × N interaction indicated by ANOVA (Table 1). The significant C × M × N interaction in this cycle reflected differences in the responses of plant N content to N application among the four C × M treatment combinations; however, no consistent pattern of responses to N application was apparent (Supplementary Figure S3). In cycle 2, mean plant N content at N1 was higher under M+ than M– conditions, but the difference between M treatments was not significant at higher N levels (Figure 2), consistent with the significant M × N interaction in ANOVA. In cycle 3, mean plant N content increased with N supply, with values at N4 significantly higher than those at N1 (Supplementary Figure S4), consistent with the significant main effect of N (Table 1).

At site K, the mean N content across treatments was 0.67% in cycle 1 and 0.79% in cycle 2. A significant main effect of M was detected in cycle 1, whereas in cycle 2, a significant main effect of N and a significant M × N interaction were detected (Table 1). Treatment means for the M and N main effects are shown in Figures 3 and 4, respectively, for both cycles. In cycle 1, plant N content was higher under M+ than under M– conditions (Figure 3). Because the significant M × N interaction qualified the main effect of N in cycle 2, pairwise comparisons among the five N levels were not performed for the main-effect plot (Figure 4). Instead, pairwise comparisons with Tukey adjustment were conducted among the 10 treatment groups defined by the M × N combinations, and the results are presented in Supplementary Figure S5. The effect of microbial inoculation depended on the N level, being evident only at N4 and not at the other N levels (Supplementary Figure S5).

Soil properties

To examine the effects of sorghum cultivation on soil, we analyzed the soil chemical properties (organic C, total N, CEC, and pH) at site CB after harvest. A three-way ANOVA including C, M, and N as factors revealed significant main effects of C on organic C and total N in cycles 2 and 3 (Table 2). Significant main effects of N and significant M × N interactions were detected for CEC in cycles 1 and 3 (Table 2). For pH, a significant C × M × N interaction was detected in cycle 2, and significant main effects of N were detected in cycles 2 and 3 (Table 2).

To facilitate comparison of the main effects of C and N on soil properties, treatment means averaged across the remaining factors are shown in Figures 5 and 6, respectively. Pairwise comparisons for the main-effect plots were performed only when the corresponding main effect was not qualified by a significant interaction (Table 2). The significant M × N interactions (cycles 1 and 3) and the significant C × M × N interaction (cycle 2) are shown separately in Supplementary Figures S6 and S7, respectively. These interactions involving M were generally small and inconsistent across cycles (Supplementary Figures S6 and S7). Organic C and total N in cycles 2 and 3 were lower in C– than in C+ plots (Figure 5). With respect to N effects, soil pH was lower at the highest N application rate (N5) than at the other N levels in cycle 3 (Figure 6). These effects on organic C, total N, and soil pH were not evident in cycle 1 (Figures 5 and 6), suggesting that the responses of these soil properties to C and N were cycle-dependent. We also compared mean values of the parameters across cycles irrespective of treatment (Table 3). For comparison, the values before cultivation were also included. Table 3 shows that organic C gradually declined with successive cycles, whereas total N increased markedly after cultivation began. Cation exchange capacity declined sharply from cycle 1 to cycle 2, coinciding with a decrease in soil pH (Table 3).

Table-2. Summary of ANOVA for properties of soil after cultivation in site CB.

Cycle	Term [1]	df [2]	Organic C			Total N			CEC			pH		
			F	*p*-value	η^2	*F*	*p*-value	η^2	*F*	*p*-value	η^2	*F*	*p*-value	η^2
1	C	1	0.1	0.754	0.00	0.5	0.489	0.01	3.4	0.074	0.04	1.8	0.186	0.04
	M	1	1.7	0.197	0.03	0.2	0.692	0.00	1.3	0.266	0.01	1.5	0.225	0.04
	N	4	1.5	0.208	0.11	0.3	0.883	0.02	3.5	0.015 *	0.15	1.3	0.274	0.12
	C:M	1	0.0	0.917	0.00	0.2	0.692	0.00	2.5	0.125	0.03	0.5	0.505	0.01
	C:N	4	0.2	0.961	0.01	0.5	0.771	0.04	2.1	0.094	0.09	0.3	0.843	0.03
	M:N	4	1.0	0.394	0.08	0.2	0.939	0.02	3.2	0.023 *	0.14	0.4	0.805	0.04
	C:M:N	4	0.6	0.694	0.04	0.6	0.642	0.05	2.1	0.095	0.09	2.0	0.109	0.17
2	C	1	16.4	0.000 **	0.23	6.5	0.014 *	0.10	0.0	0.969	0.00	0.2	0.656	0.01
	M	1	0.1	0.720	0.00	0.5	0.497	0.01	0.2	0.679	0.00	4.7	0.035	0.11
	N	4	1.0	0.417	0.06	0.7	0.567	0.04	1.0	0.404	0.08	5.6	0.001 *	0.36
	C:M	1	1.6	0.215	0.02	1.4	0.243	0.02	3.3	0.078	0.06	1.8	0.191	0.04
	C:N	4	0.6	0.638	0.04	2.5	0.059	0.15	0.4	0.836	0.03	0.2	0.945	0.02
	M:N	4	0.6	0.663	0.03	0.8	0.525	0.05	1.0	0.444	0.07	0.5	0.724	0.05
	C:M:N	4	0.7	0.584	0.04	0.7	0.613	0.04	0.3	0.872	0.02	3.1	0.026 *	0.24
3	C	1	11.3	0.002 **	0.15	10.0	0.003 **	0.14	1.2	0.274	0.02	3.6	0.065	0.08
	M	1	0.1	0.731	0.00	0.1	0.802	0.00	0.9	0.338	0.01	3.2	0.079	0.08
	N	4	1.4	0.253	0.07	1.2	0.333	0.07	2.9	0.035 *	0.15	4.6	0.004 **	0.31
	C:M	1	0.6	0.450	0.01	0.0	1.000	0.00	0.8	0.364	0.01	0.1	0.702	0.00
	C:N	4	2.2	0.081	0.12	2.3	0.080	0.13	1.1	0.365	0.06	0.8	0.534	0.07
	M:N	4	2.0	0.114	0.11	1.3	0.285	0.07	3.1	0.025 *	0.17	0.4	0.823	0.04
	C:M:N	4	0.3	0.858	0.02	0.8	0.545	0.04	1.0	0.413	0.05	1.6	0.200	0.14

[1] C: compost, M: microbial inoculant, N: N dosage
[2] degree of freedom
* Significant effect at $p < 0.05$ level; ** Significant effect at $p < 0.01$ level

Table-3. Properties of soil before and after cultivation in Site CB.

Sample	Organic C (%)		Total N (%)		CEC (cmol kg^{-1})		pH	
Before cultivation	2.2		0.04		55.1		6.4	
After cycle 1	2.7 ± 0.34	c	0.23 ± 0.02	b	41.8 ± 4.04	c	6.3 ± 0.16	b
After cycle 2	2.5 ± 0.27	b	0.20 ± 0.02	a	9.8 ± 0.53	a	5.7 ± 0.19	a
After cycle 3	2.3 ± 0.27	a	0.21 ± 0.02	a	18.8 ± 1.40	b	5.8 ± 0.19	a

Values are the mean of two plots for before cultivation, and the mean ± SD of 60 plots (collapsed across C, M, and N treatments) for after cycles 1–3.

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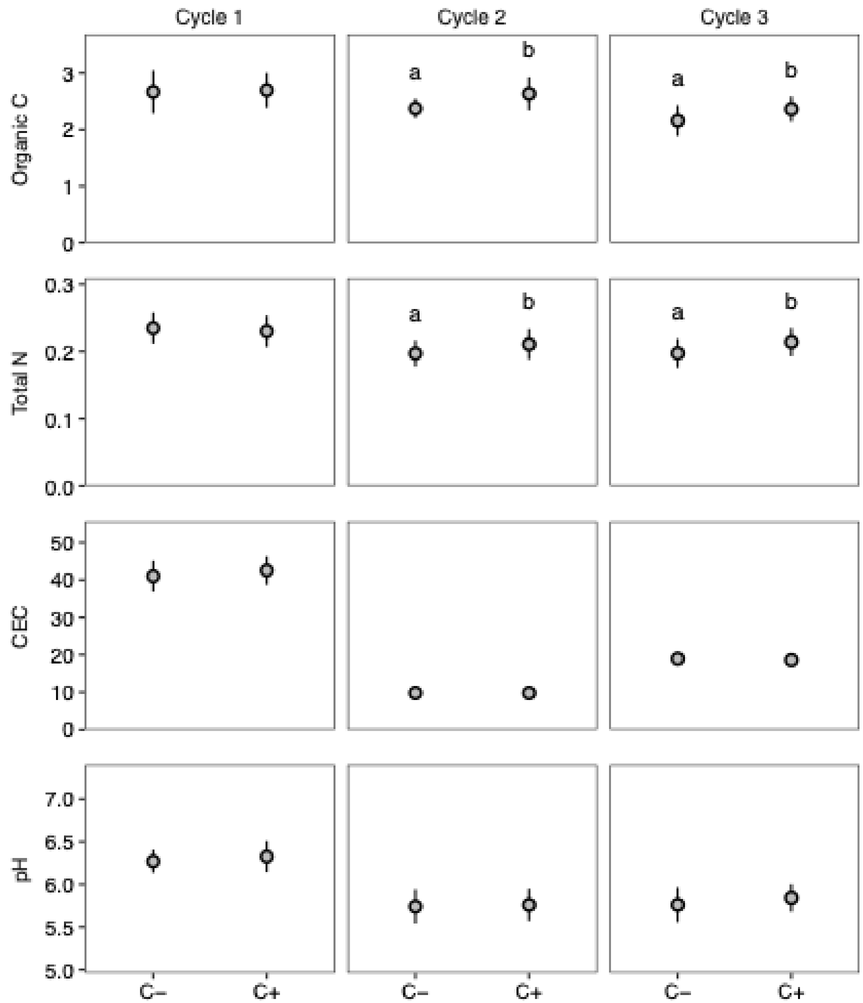

Figure-5. Soil chemical properties at site CB (main effect of C).
Points show observed means (n = 30) with standard deviations for the two compost treatment groups (C– and C+), averaged across microbial inoculation (M) and N application rates. Post-hoc pairwise comparisons with Tukey adjustment were performed only for cycle–parameter combinations in which the main effect of C was significant and was not qualified by a significant interaction involving M in the ANOVA (Table 2). Different letters indicate significant differences between C– and C+ within each cycle ($p < 0.05$), based on Tukey-adjusted comparisons of estimated marginal means from a three-way ANOVA including C, M, and N as factors.

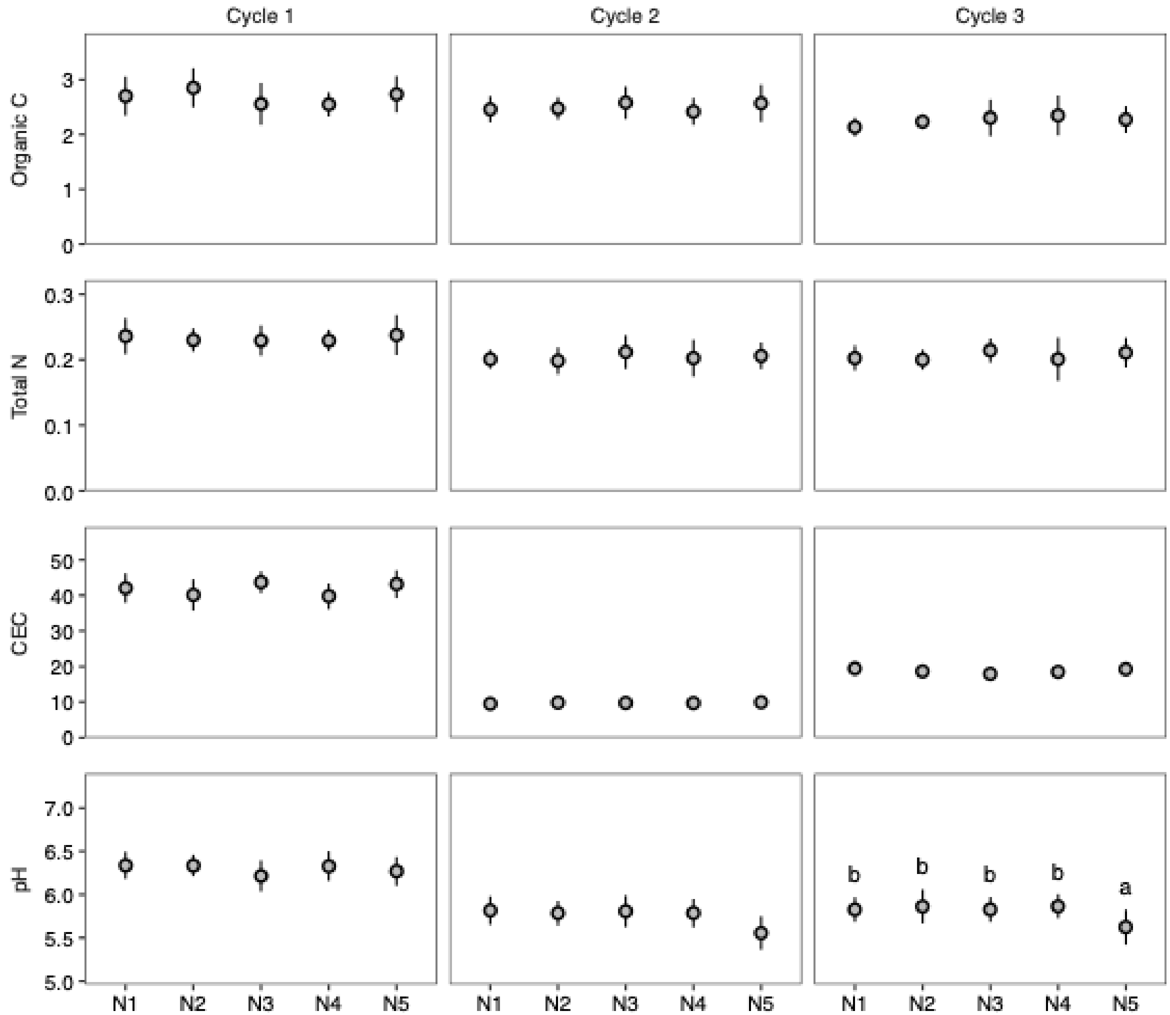

Figure-6. Soil chemical properties at site CB (main effect of N).
Points show observed means (n = 12) with standard deviations for the five N application rates averaged across compost (C) and microbial inoculation (M) treatments. Post-hoc pairwise comparisons with Tukey adjustment were performed only for cycle–parameter combinations in which the main effect of N was significant and was not qualified by a significant interaction involving N in the ANOVA (Table 2). Different letters indicate significant differences among N application rates within each cycle ($p < 0.05$), based on Tukey-adjusted comparisons of estimated marginal means from a three-way ANOVA including C, M, and N as factors.

Discussion

Cultivation on marginal lands is subject to various constraints, such as climate and water supply, whereas improving soil fertility is more amenable to intervention. This study examined the growth performance of sorghum as a biomass crop under various fertilization regimes at two sites: site CB in West Java and site K in Central Kalimantan.

The results confirmed that N application significantly affected sorghum growth across both sites and multiple cycles (Table 1), consistent with many previous studies (Afzal et al., 2013; Bartzialis et al., 2020, 2023; Ikanovic et al., 2014; Jankovic et al., 2012; Maughan et al., 2012; Maw et al., 2017). The N effects were also associated with generally larger effect sizes (partial η^2) than those of compost or microbial inoculation (Table 1), indicating that N application was the dominant treatment factor influencing sorghum production under the present experimental conditions. For DWB, however, these effect sizes further suggest that the responses to N differed between the two sites. At site CB, the effect of N was large in cycle 1 but became smaller in cycles 2 and 3 (Table 1). Meanwhile, at site K, relatively large N effects were maintained across both cultivation cycles (Table 1). This pattern is consistent with the lower inherent fertility of site K, suggesting that biomass production at this site remained more responsive to N inputs across cultivation cycles than at site CB.

DWB in plots without N fertilizer (N1) was consistently the lowest, at least at site CB (Figures 1 and 2). By contrast, the highest N application rate (N5), corresponding to the recommended level in conventional sorghum cultivation (Kansas State University, 2013; Vanderlip, 1993), did not necessarily outperform the moderate application rates (N3–N4). This suggests that while N fertilizer application is critical for achieving good yields in sorghum production in marginal grasslands, the optimal rate may be lower than the conventional standard, which has important implications for reducing environmental impact and ensuring sustainability.

This study also assessed how soil amendments, specifically compost (C) and a microbial inoculant (M), influenced the effects of fertilizers. At site CB, significant C × N interactions were detected for N content in cycle 1 and SC in cycle 2, while a significant C × M × N interaction was detected for N content in cycle 1 (Table 1). For N content in cycle 1, compost appeared to accentuate the response to N application, as reflected by the greater contrast between N1 and N4/N5 under C+ than under C– (Figure 1). Conversely, for SC in cycle 2, compost attenuated the differences across N levels (Figure 1). However, these interaction patterns were inconsistent across cycles (Figure 1). Taken together, the effect of compost on yield-related traits was not clearly demonstrated at site CB. Meanwhile, compost application was found to help maintain higher soil organic C and total N in cycles 2 and 3 (Figure 5). These results may reflect the fact that improvements in soil properties such as organic C and total N contribute to maintenance of long-term soil fertility but may not immediately translate into increased biomass production during the relatively short experimental period. At site K, compost was applied to all plots to improve soil physical properties; thus, its specific effect could not be evaluated.

Regarding microbial inoculants, M × N interactions were observed for DWB in cycle 1 and N content in cycle 2 at site CB (Table 1). For DWB in cycle 1, the presence of M appeared to reduce the difference between the unfertilized (N1) and high-N (N4 or N5) plots (Figure 2). Similarly, for N content in cycle 2, M showed a pronounced influence in unfertilized plots (Figure 2), indicating that M may support growth under low-N conditions. However, these M × N interactions were restricted to specific traits and cycles, suggesting that the effects of microbial inoculation were not consistently observed (Table 1, Figure 2). At site K, which has nutrient-poor soils, the main effects of M were detected in cycle 1 for DWB, TGW, and N content (Table 1). These parameters were higher in M+ plots than in M– plots in cycle 1 (Figure 3).

Since microbial inoculants can promote plant growth through hormone synthesis, N fixation, and the solubilization of phosphate and K (Alori and Babalola, 2018; Ansari et al., 2024; Gonçalves et al., 2025; O'Callaghan et al., 2022; Shahwar et al., 2023), their effectiveness is likely to depend on soil nutrient status and other environmental conditions. Accordingly, their effects may be more pronounced in nutrient-poor soils than in relatively fertile soils, as noted by Kazungu et al. (2023). This may explain why positive responses were more evident at site K than at site CB (Figures 2 and 3) and were limited or inconsistent under some conditions, particularly under high N application (Figure 2). The positive effect was not evident in cycle 2 at site K, where overall DWB was much lower than that in cycle 1, suggesting that other growth-limiting factors may have masked potential microbial benefits (Figure 3).

To make sorghum cultivation on unused grasslands a viable strategy for mitigating climate change, it is essential to consider not only yield but also environmental impacts and sustainability. Soil analyses at site CB indicated that soil organic C temporarily increased after cycle 1, likely due to inputs of sorghum root biomass, but then declined gradually with successive cycles (Table 3). Although total N initially increased after cultivation began, presumably due to fertilizer inputs, this increase was not maintained during subsequent cultivation cycles (Table 3). Together, these changes suggest a gradual depletion of soil organic matter over successive cultivation cycles. Cation exchange capacity declined sharply from cycle 1 to cycle 2, likely due to a reduction in negative charges associated with the decrease in pH (Table 3). Significant effects of N on soil pH were detected after cycles 2 and 3 (Table 2).

Plots receiving the highest N application (N5) generally showed lower pH values than the other treatments in cycles 2 and 3 (Figure 6), possibly due to enhanced nitrification and base leaching. These observations suggest a gradual deterioration of soil chemical properties under continuous sorghum cultivation. A decline in CEC may decrease the soil capacity to retain exchangeable nutrients, thereby increasing nutrient loss under the high-rainfall conditions typical of tropical marginal lands. In addition, soil acidification may reduce phosphorus availability and alter soil microbial communities, thereby leading to a gradual decline in soil fertility. Without appropriate management, these changes could ultimately undermine the long-term sustainability of continuous sorghum cultivation.

Taken together, these findings indicate that converting alang-alang grasslands to sorghum fields risks depleting soil organic matter and reducing long-term soil productivity. Importantly, compost application significantly helped maintain higher levels of organic C and total N in the soil after cycles 2 and 3 (Figure 5). This suggests that even where compost has little direct effect on yields (as at site CB, Table 1), it remains a vital practice for sustainability. Nevertheless, because the beneficial effects of compost on soil properties were rather limited (Figure 5), additional soil management practices may also be required. For example, periodic liming to counteract soil acidification, together with crop rotation or intercropping with leguminous crops, may help maintain long-term soil fertility, although these practices were not evaluated in the present study.

Wiloso et al. (2020) conducted an LCA of substituting 5% of coal with sorghum pellets in coal-fired power generation in Indonesia and reported that the practice can achieve a net reduction in greenhouse gas (GHG) emissions provided sorghum biomass yields reach 48 t ha^{-1} $year^{-1}$. In this study, maximum yields at site CB were 302.1, 247.1, and 235.1 g $plant^{-1}$ in cycles 1, 2, and 3, respectively (Supplementary Table S4). Taking planting density into account, these values correspond to 32, 26, and 25 t ha^{-1}. Assuming two cropping cycles per year, annual sorghum biomass production at the site could hence reach 50–64 t ha^{-1}, sufficient to contribute to net GHG reductions from the LCA perspective. In contrast, at site K, maximum yields were 224.9 and 150.3 g $plant^{-1}$ in cycles 1 and 2, which corresponds to 24 and 16 t ha^{-1}, respectively. Thus, even with two annual harvests, yields at site K may not reach the 48 t ha^{-1} $year^{-1}$ threshold. As noted by Tang et al. (2018), sorghum cultivation on marginal lands is strongly influenced by soil fertility, and on excessively poor soils, it may not represent a realistic option for energy production.

The present results indicate that on soils with at least moderate fertility, such as site CB, currently unused degraded grasslands can produce sufficient biomass yields to meet LCA thresholds for GHG reduction. However, it is important to recognize that environmental evaluation (GHG reduction potential) and economic evaluation (cost competitiveness relative to coal) are distinct issues. Currently, the cost of power generation from sorghum pellets is approximately double that of coal (Bappenas Indonesia, 2019). Mahmoody et al. (2021) noted that this gap exists partly because limited yields increase the per-ton costs of fixed processes such as drying, palletization, and transport. Thus, further yield improvement can directly help offset the cost asymmetry between sorghum pellets and conventional fossil fuels such as coal. In addition to fertilization and soil management, key strategies include breeding high-yielding varieties, improving processing technologies, and establishing efficient local supply chains. Accumulating field-based empirical data, such as in this study, and combining them with LCA and economic assessments will enable a more accurate evaluation of the environmental and economic impacts of sorghum biomass. Ultimately, such results can inform policies and investment strategies to support the transition to low-carbon energy.

Conclusion

The results from the two field sites demonstrated that sorghum cultivation can achieve meaningful biomass production even on degraded tropical grasslands with moderate soil fertility. Nitrogen fertilization was confirmed to affect biomass production, but the required level could be lower than conventional recommendations, implying a potential for reducing both costs and environmental impacts. Compost and microbial inoculants had limited direct effects on yield, but compost was suggested to be important for maintaining soil conditions. The maximum yield at the moderately fertile site (50–64 t ha^{-1} $year^{-1}$) reached the threshold for net greenhouse-gas reduction estimated by a previous study (Wiloso et al. 2020). In contrast, yields on the nutrient-poor sandy soil were lower (16-24 t ha^{-1} $year^{-1}$), indicating that productivity depends strongly on inherent soil fertility. Overall, this study provides field-based empirical data defining the attainable yield range of sorghum under tropical marginal land conditions. Such quantitative benchmarks can support techno-economic evaluations of sorghum-based bioenergy systems and inform policy decisions on the utilization of degraded lands for renewable energy production.

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Data is available from the corresponding author upon reasonable request.

Contribution of Authors
Rachmadiyanto AN, Lestari R & Kobayashi M: Conceptualization of research, data collection and analysis.
Rachmadiyanto AN, Lestari R, Magandhi M & Zulkarnaen RN: Designed research methodology.
Lestari R, Tyas KN & Kobayashi M: Investigation.
Rachmadiyanto AN, Lestari R, Ragamustari SK & Kobayashi M: Writing of original draft.
Rachmadiyanto AN, Lestari R, Tyas KN, Magandhi M, Usmadi D, Zulkarnaen RN, Helmanto H, Damayanti F, Rivai RR, Primananda E, Husaini IPA, Sudiana IM, Ragamustari SK & Kobayashi M: Writing, review and editing.
Lestari R, Sudiana IM & Kobayashi M: Funding acquisition and literature review
Magandhi M, Usmadi D, Zulkarnaen RN, Helmanto H, Damayanti F, Rivai RR, Primananda E & Husaini IPA: Resources provision and data interpretation.
Sudiana IM & Kobayashi M: Supervision and data interpretation.
All authors read and approved the final draft of the article.

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