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Soil fertility and performance of sorghum in monoculture and integrated with Piatã grass using biofertilizer as a nutritional source

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Abstract: The objective was to evaluate the effect of biofertilizer obtained through the anaerobic bio-digestion of poultry litter on the performance of sorghum BRS 610 in monoculture and integrated, and its impacts on the chemical attributes of the soil. The experiment was carried out following the premises of a randomized block design, in split-plots, with five levels of biofertilizer (0; 10; 20; 30; 40 m^3 ha^{-1}) in two cropping systems (sorghum monoculture and Piatã grass + sorghum intercropping). The agronomic characteristics of the biofertilizer levels in the two cropping systems were assessed, as well as the influence on the soil's chemical attributes. The use of biofertilizers affected forage production, with quadratic effects on the monoculture and linear effects on the intercropping system. For both production systems, the proportion of leaves and stems, as well as the number of plants, showed decreasing linear effects as the application of biofertilizers increased. In addition, it increased the levels of P and K^+, with the best results at levels of 40 m^3 ha^{-1} on both production systems. The pH and Al^{3+} showed variations depending on the depth and level Applied. The use of biofertilizer from the anaerobic bio-digestion of chicken litter compromises the performance of sorghum in intercropping, but improves the production of green and dry mass in monoculture up to a level of 21.54 m^3 ha^{-1}, as well as the levels of P and K^+ in the soil.

Keywords: Biofertilizer; crop-livestock integration; organic fertilization; *sorghum bicolor*; *Urochloa brizantha* cv. Piatã.
Abbreviations: ATP_adenosine triphosphate; AF_as fed; CEC_cation exchange capacity; CV_coefficient of variation; DM_dry matter; LAI_leaf area index; L:S_leaf : stem ratio; LSM = liquid swine manure; OM_organic matter SB_sum of bases.

Introduction

Agriculture and livestock production in Brazil have been exploring sustainable alternatives for decades to continue expanding minimizing the need for new land while ensuring socio-environmental responsibility (Souza et al., 2022). Concerns about the environmental impacts of the agricultural sector have become fundamental in the modernization of production systems, due to the impacts of inadequate management of inputs and natural resources, which can reduce biodiversity, and cause erosion and contamination of soils and rivers (Adedibu, 2023).

In this context, intercropping has been considered one of the most sustainable and competitive techniques for the efficient use of land resources, resulting in a reduction in the costs of implementing and maintaining the surrounding crops, and improving the physical, chemical and biological conditions of the soil (Pariz et al., 2009). Allen et al. (2007) found in a crop-livestock integration system, a 40% reduction in the use of nitrogen fertilizers and a 25% reduction in the use of irrigation water, as well as improved microbiological activity in the soil and retention of more rainwater than in a monoculture system. With the contribution of the integration system, farmers need new viable alternatives that can replace or reduce the use of chemical fertilizers (Silveira Junior et al., 2015), since they are one of the main contributors to production costs and originate from non-renewable sources. Therefore, organic wastes, in particular biofertilizers, are a favorable alternative, as they contain nutrients in organic and inorganic form, making them an excellent source of fertilizer, which contain most of the essential nutrients for plants (Araújo et al., 2008; Areeshi, 2022).

Table 1. Chemical characteristics of poultry litter biofertilizer and equivalent nutrient values according to application levels.

Application	N	P_2O_{5total}	$K_2O_{soluble}$	Ca	Mg	O.M	Moist.*	MM**	Na
	-------------------		%	---------------------					ppm
1st	0.51	0.07	0.48	0.29	0.10	5.50	91	3.50	640.0
2nd	0.49	0.06	0.47	0.27	0.07	4.00	93	3.00	620.0
Levels	Kg ha^{-1}								
10 m^3 ha^{-1}	50	6.5	47.5	28.0	8.5	-	-	-	-
20 m^3 ha^{-1}	100	13.0	95.0	56.0	17.0	-	-	-	-
30 m^3 ha^{-1}	150	19.5	142.5	84.0	25.5	-	-	-	-
40 m^3 ha^{-1}	200	26.0	190.0	112.0	34.0	-	-	-	-

*Moisture; ** Mineral Matter.

Table 2. Effect of using biofertilizers in two cropping systems.

Systems	AF Yield	DM Yield	Leaf	Stem	Panicle	Dead Material
	Mg ha^{-1}		%			
Monoculture	20.59 a	5.50 a	12.02	49.46 b	33.16 a	7.49 b
Intercropping	15.75 b	4.40 b	11.89	54.97 a	24.87 b	8.68 a
CV (%)	15.38	16.17	13,82	8.26	17.76	19.76

Means followed by the same letter do not differ from each other according to the Tukey's test at 5% probability.

Poultry litter is an example of raw material to produce biofertilizer with high nutrient availability, as it contains the main nutrients (nitrogen, calcium, phosphorus, potassium and magnesium) in concentrations that are suitable for plant development. The bio-digestion process makes many of these nutrients easily accessible, enhancing its use as a nutrient source. Additionally, poultry litter is affordable and easily available (Ajaweed et al., 2022).

The purpose of this study was to evaluate the effect of biofertilizer from poultry litter on the agronomic characteristics of sorghum (BRS 610) intercropped with *Urochloa brizantha* cv Piatã or in monoculture, as well as checking the effects on the soil's chemical attributes.

Results

Agronomic characteristics of sorghum

Significant differences ($p \leq 0.05$) were found between the two cropping systems regarding production variables and the proportion of dry mass components of sorghum, except for the proportion of leaves (Table 2). Monoculture showed higher production of green mass (30.73%) and dry mass (25%). In addition, higher proportions of panicle (33.33%), and lower proportions of stem (11.14%) and dead material (15.89%), were observed in the monoculture system.

The use of biofertilizers affected the production of green mass (Figure 1a) and dry mass (Figure 1b), with a quadratic effect in the monoculture, showing optimum levels of 21.54 and 20.96 m^3 ha^{-1} of biofertilizer, corresponding to the production of 25.62 and 6.64 Mg ha^{-1} of green and dry mass, respectively. In the intercropping, the effect was linearly decreasing, with a reduction of 151.8 and 44.30 kg of green and dry biomass, respectively, for every 1m^3 ha^{-1} of biofertilizer used.

The proportion of leaves (Figure 1c) and stem (Figure 1d) decreased linearly as the level of biofertilizer increased in both cropping systems, showing reductions of 1.13% and 2.22% for the monoculture and 1.16% and 1.5% for the intercropping for every 10 m^3 ha^{-1} of biofertilizer used, respectively. The proportion of panicles increased linearly (Figure 1e), with increases of 2.87% and 3.72% for the monoculture and intercropping, respectively. In both systems, the proportion of dead material showed a quadratic effect from the application of biofertilizer, with the lowest rate at 27.77 m^3 ha^{-1} of biofertilizer in the monoculture and 29.05 m^3 ha^{-1} in the intercropping (Figure 1e).

There was a significant effect ($p \leq 0.05$) of the cropping system on stem diameter, height and brix (Table 3). However, there were no significant differences ($p > 0.05$) between the two cropping systems regardind the vriables LAI, leaf : stem ratio and number of tillers per plant. Monoculture showed greater height (5.22%) and stem diameter (15.63%) and lower brix (8.10%) when compared to the intercropping.

For leaf : stem ratio (Figure 2a) and LAI (Figure 2b), there was a quadratic effect in the monoculture with the optimum levels of 8.13 and 20.4 m^3 ha^{-1} of biofertilizers, which corresponds to 0.27 for the leaf : stem ratio and 1.58 for LAI,, and a decreasing linear effect in the intercropping.

In the monoculture, the diameter of the stem (Figure 2e) and the brix degree (Figure 2c) showed quadratic effect, and the number of plants (Figure 2d) showed decreasing linear effect. The optimum level was 23.9 m^3 for a 13.52% increase in stem diameter, and 1.86 m^3 ha^{-1} of biofertilizer for a production of 7.22 brix degrees, with a reduction of 1.67 plants m^{-2} for every 10 m^3 ha^{-1} of biofertilizer applied.

In the intercropping with Piatã grass, there was a decreasing linear effect for number of plants (Figure 2d) and brix degree (Figure 2c), with a reduction of 1.67 plants m^{-2} and 0.973 brix degrees for every 10 m^3 ha^{-1} of biofertilizer.

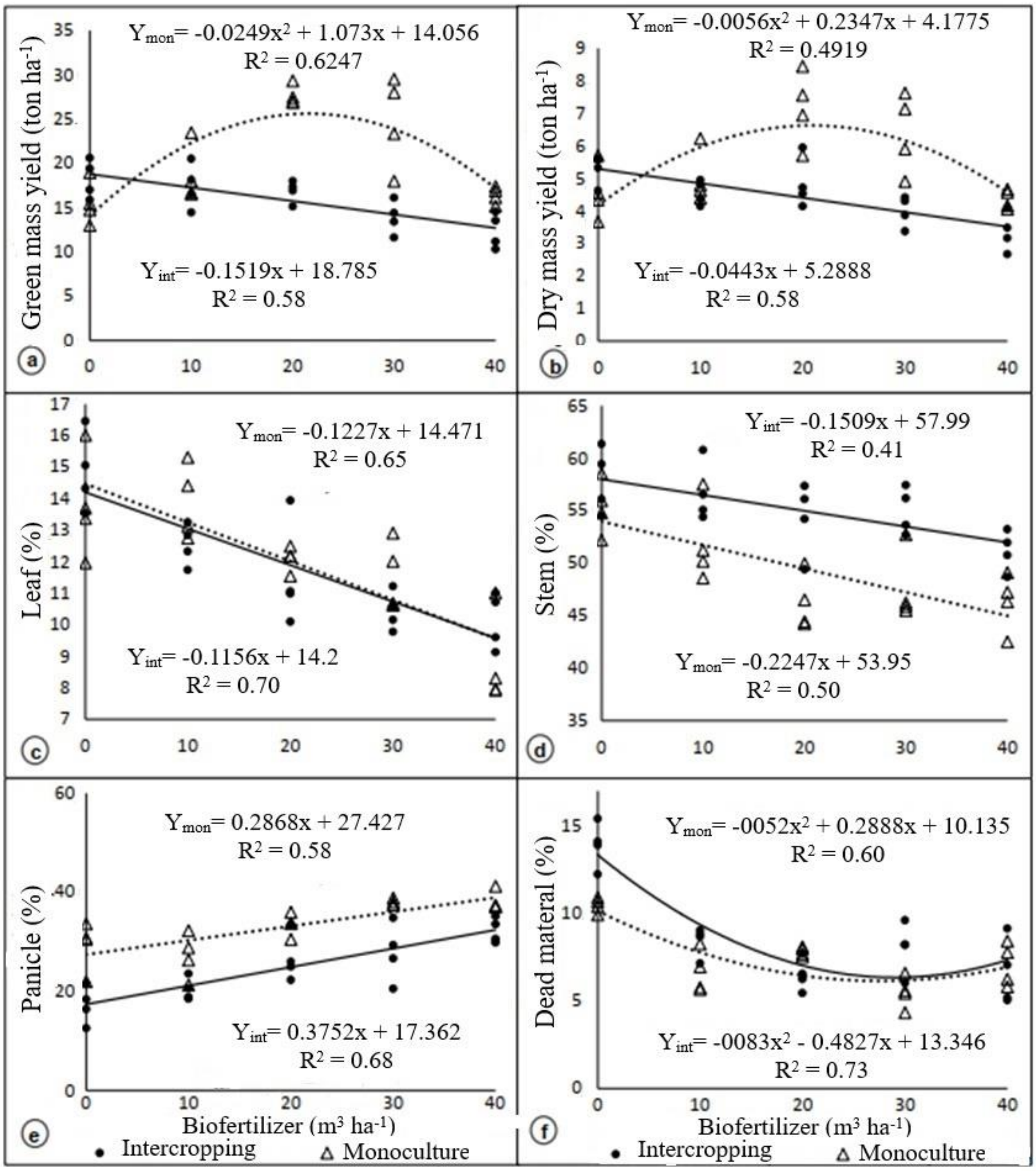

Figure 1. Yield of green mass (a), dry mass (b) and morphological components leaf (c), stem (d), panicle (e) and dead material (f) of sorghum as a function of the levels of biofertilizers and cropping systems: intercropping with Piatã grass and monoculture.

Soil chemical attributes

The chemical attributes of the soil were significantly affected ($p \leq 0.05$) at the depths of 0-7 cm and 7-15 cm regarding the contents of Ca^{2+}, Mg^{2+}, P, K^+, OM, SB and $CEC_{effective}$, with better responses in the superficial layer (Figure 3 and 4). Meanwhile, variables such as: pH_{CaCl}, Al^{3+} and m (%) had no significant differences ($p > 0.05$) at both depths.

The soil pH in the 0-7 cm layer showed no significant differences ($p > 0.05$) between cropping systems and levels of biofertilizers, but there was a significant difference ($p \leq 0.05$) in the 7-15 cm layer with caused by the use of biofertilizers, with higher values at levels of 10 to 30 m^3 ha^{-1} (Figure 3 and 4).

The exchangeable Ca^{2+} in the soil was influenced by the levels of biofertilizers ($p \leq 0.05$) in the surface layer (0-7 cm deep), with no difference between cropping systems ($p > 0.05$) (Figure 3). The best response (5.02 $cmol_c dm^{-3}$) was obtained with 40 m^3 ha^{-1} of biofertilizer. The Mg^{2+} content did not vary with the levels of biofertilizer ($p > 0.05$) but differed between depths and cropping systems ($p \leq 0.05$), with the lowest values in the 0-7 cm layer.

There was effect of interaction ($p \leq 0.05$) between levels of biofertilizer and cropping systems on the content of Al^{3+} in the 0-7 cm layer, which showed lower values in the intercropping system at levels of 20 and 30 m^3 ha^{-1} of biofertilizer. In the 7-15 cm layer, Al^{3+} had significant effect ($p \leq 0.05$) of the levels of biofertilizer, showing the highest values in the absence of biofertilizer.

The application of biofertilizer increased the P content in the soil in both layers (Figures 3 and 4), with better values ($p \leq 0.05$) when 40 m^3 ha^{-1} of biofertilizer was used (3.87 and 2.88 mg dm^{-3} for the 0-7 and 7-15 cm layers, respectively). K+ contents were influenced by the application of biofertilizer and by the cropping systems ($p \leq 0.05$) at both depths, with higher concentrations at levels of 30 to 40 m^3 ha^{-1} of biofertilizer, and better responses in the monoculture.

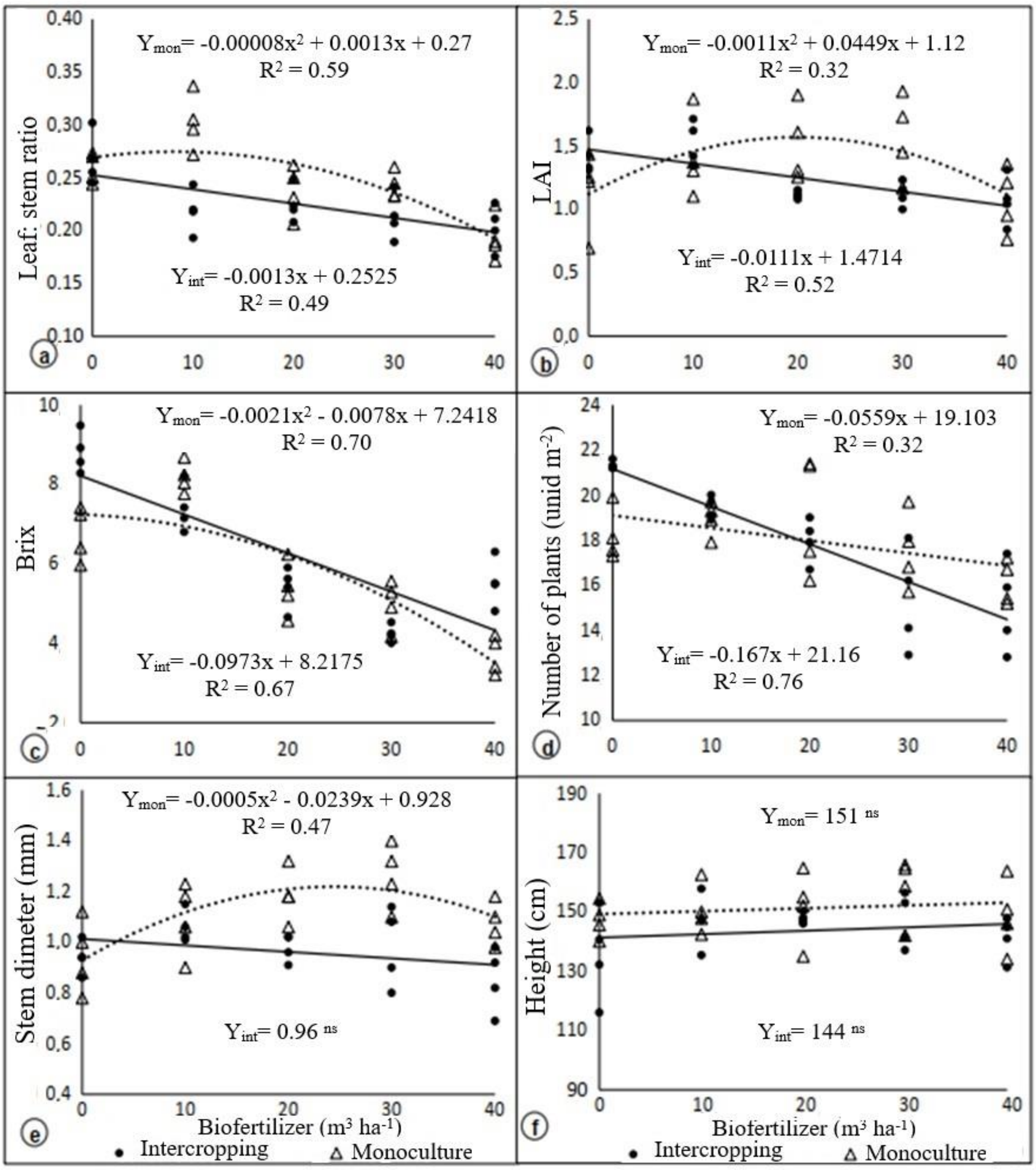

Figure 2. Effect of using biofertilizers on the variables LAI, leaf/stem ratio, brix, number of plants, stem diameter and height of sorghum in monoculture system or intercropped with Piatã grass.

The organic matter content was affected by the cropping systems ($p \leq 0.05$), with the intercropping presenting higher values (2.39 and 2.47 g dm^{-3} in the 0-7 and 7-15 cm layers, respectively). In the 0-7 cm layer, there was a significant effect of interaction ($p \leq 0.05$) between levels of biofertilizer and cropping systems, with the best results in the intercropping system for levels of 30 and 40 m^3 ha^{-1} of biofertilizer (Figures 3 and 4). In the 7-15 layer, the organic matter content decreased significantly ($p \leq 0.05$) with the application of 10 and 20 m^3 ha^{-1} of biofertilizer.

Discussion

The results showed that the production of sorghum in the monoculture system was higher than in intercropping. This difference was expected, as the lower yield in intercropping can be attributed to the reduction in plant density and greater competition for nutrients, water and light (Glaze-Corcoran et al., 2020; Sadafzadeh et al., 2023). Mota (2010) studied sorghum in monoculture and intercropped with *Urochloa brizantha* cv. Xaraes, *Megathyrsu maximum* cv. Tanzania and *Andropogon gayanus* cv. Planaltina, and also observed a 28% reduction in the productivity of sorghum when it was intercropped with grasses.

The interference of grasses in the intercropping system with annual crops has been evidenced by several authors (Javanmard et al., 2020; Sadafzadeh et al., 2023). In this system, the objective is to initially favor the crop for maximum production until harvest, benefitting the grass later.

The cropping system significantly affects some morphological and physiological characteristics of grain sorghum (Table 4 and 5). The average proportion of leaves was 11.95%, which is considered low, resulting in a low leaf:stem ratio (0.24) in both systems (Table 5). The low L:S ratio is directly linked to forage quality, as evidenced by the high correlation with leaf proportion and brix (R=0.82 and 0.53, respectively). The decrease in the participation of leaves in the total forage yield compromises its quality and eventual intake by animals (Sarmento et al., 2010). Pinho et al. (2006) reported leaf, stem and

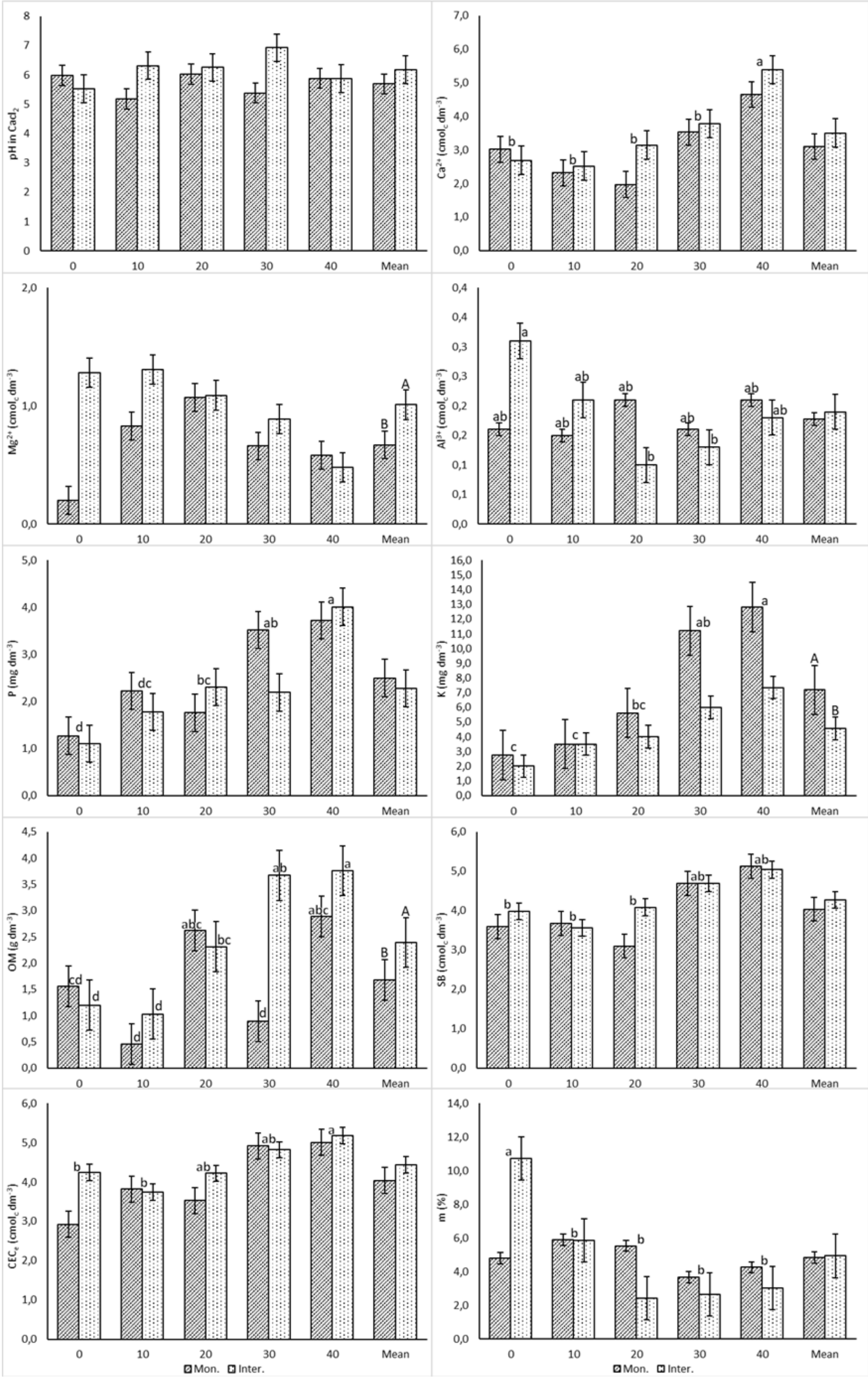

Figure 3. Chemical attributes of the soil in intercropping system (sorghum and Piatã grass) and sorghum monoculture, cultivated with different levels of biofertilizers in the 0 - 7 cm depth layer. Means followed by the same letter do not differ from each other according to the Tukey's test at 5% probability.

panicle percentages of 22.3%, 44.3% and 33.4%, respectively, which is similar to the results found in the present study with the BRS 610 hybrid.

In the intercropping of grain sorghum with Piatã grass, the sorghum plants were shorter, had a higher proportion of dead material and a smaller stem diameter, probably as a compensatory mechanism for the higher population density of the crops and interspecific competition between plants for nutrients, water and light (Ribeiro et al., 2015). However, intercropping increased the brix degree, suggesting that this system can induce a higher production of soluble sugars, which is interesting for silage, as high values can result in intense alcoholic fermentation (Ribeiro et al., 2010). In addition, integration aims to complement the production of both crops, as there will be grain production from the crop, and the forage can be used to feed animals in the off-season (Oliveira et al., 2020).

The sorghum monoculture showed limited production efficiency with the use of biofertilizer, while the intercropping showed lower efficiency (Figure 1a and 1b). Despite the good concentration of N in the fertilizer (Table 1), the results indicate low availability for the plants, probably due to immobilization. The biofertilizer was applied 25 and 44 days after germination, and phytotoxic effects were observed in Piatã grass and in the sorghum soon after application, such as chlorosis

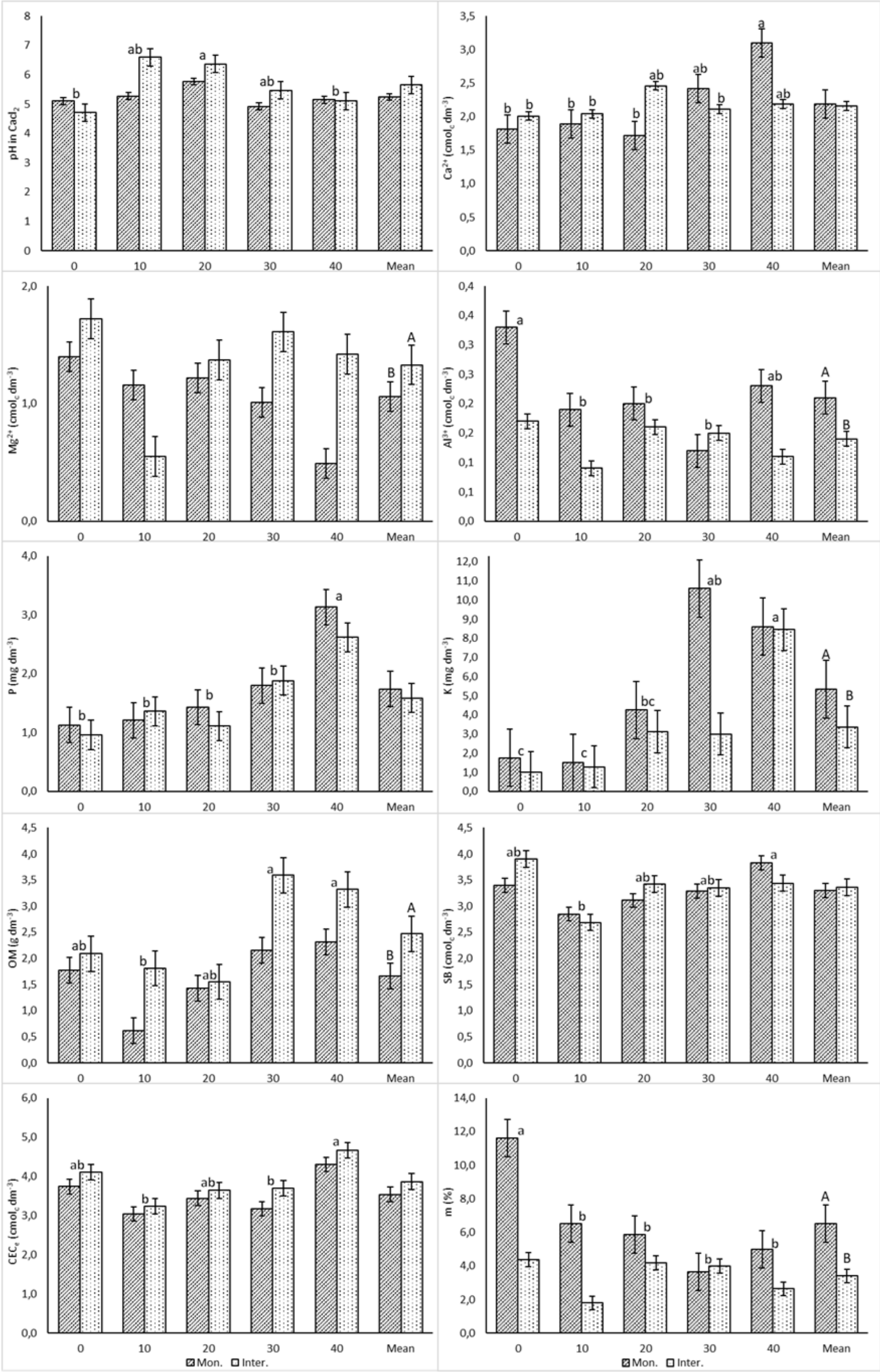

Figure 4. Chemical attributes of the soil in intercropping system (sorghum and Piatã grass) and sorghum monoculture, cultivated with different levels of biofertilizers in the 7 - 15 cm depth layer. Means followed by the same letter do not differ from each other according to the Tukey's test at 5% probability.

and necrosis, with later plant death at higher levels. High concentrations of cations (Table 3) and microorganisms in the biofertilizer can negatively affect production performance when applied at high levels, affecting processes such as electron transport, ATP, and translocation of water and nutrients, as well as compromising the plant's defense system, directly affecting its morphology (Chaudhary et al., 2022).

However, at low levels, biofertilizers can strengthen plant resistance (Kupper, et al., 2009), which explains the low values observed in the variables studied (stem diameter, leaf : stem ratio, LAI, green and dry mass production, brix, proportion of leaf and stem).

Some authors (Barrera, 2003; Silva et al., 2015) report that the use of biofertilizers, with a slightly alkaline pH (7 - 8) and high amounts of basic cations, can contribute to improving the soil pH. According to Neves Neto et al. (2012), an increase in soil pH raises the concentration of Ca^{2+}, Mg^{2+} and K^{+}. In the present study, levels of biofertilizer of 30 and 40 m^3 ha^{-1} increased the sum of base ($p \leq 0.05$) in the 0 - 7 cm layer (Figure 3).

In the 0-7 cm layer, with 40 m^3 ha^{-1} of biofertilizer, the Ca^{2+} content was considered high (5.02 $cmol_c$ dm^{-3}), as it was greater than 4 $cmol_c$ dm^{-3} in the soil. For a good balance of nutrients, the proportions of Ca^{2+}, Mg^{2+} and K^{+} should be 12-4-1, respectively, so that plant absorption is not impaired (Malavota, 2006). However, the observed concentrations of Ca^{2+}, Mg^{2+}

and K^+ in the present study indicate competition for adsorption and absorption sites in the soil and by the plant roots, which may have contributed to the low production performance of sorghum (Table 4, 5; Figure 1 and 2).
Mg^{2+} showed a negative correlation with Ca^{2+} (-0.55), suggesting competition between these elements for absorption sites, with Mg^{2+} values in the 0-7 cm layer around 30% lower than in the 7-15 cm layer. Medeiros et al. (2008), studied different ratios of Ca^{2+} and Mg^{2+} in the nutrition and development of corn, and showed that increasing the Ca^{2+} : Mg^{2+} ratio inhibited the absorption of Mg^{2+} and K^+ by the plants, causing a reduction in dry matter yield and corn height.
The higher proportion of Mg^{2+} observed in the intercropping system may be due to the greater amount of organic matter ($p \leq 0.05$). On the other hand, the higher concentration of Mg^{2+} in deeper layers may be attributed to the high Ca^{2+} : Mg^{2+} ratio, which may have led to the displacement of Mg^{2+} to deeper layers (Corrêa et al., 2007). Another aspect that may lead to a decrease in Mg^{2+} in the soil may be related to the soluble organic acids present in the biofertilizer and soil organic matter, which may form complexes with Mg^{2+}, favoring its precipitation in the soil profile.
The reduction in the content of Al^{3+} in the 7-15 cm layer in the intercropping system can be attributed to the increase in organic matter, which reduces the toxic effect of Al^{3+} and to the improvement in the Ca^{2+} : Mg^{2+} ratio (Salet et al., 1999). In addition, the lower concentrations of Al^{3+} found in the biofertilizer treatments are due to the increase in the sum of bases (Ca^{2+}, Mg^{2+}, K^+, Na^+) which contributed to the precipitation of Al^{3+} into deeper layers. Meanwhile, the lower K^+ values in the intercropping system may be related to the greater competition between the crops (sorghum and grass), but this response may change over time due to the return of K^+ to the system through the mineralization of organic matter, as it is one of the most recycled nutrients (Rodrigues et al., 2008).
The influence of the cropping system on the concentration of OM observed in this study corroborates Schaefer et al. (2012), who evaluated the physical attributes and organic carbon of the soil in monoculture and intercropped forage systems and found a higher carbon stock in the 0-5 cm layer in the intercropping, due to the greater contribution of organic matter from the surrounding crops (shoot biomass and roots).
The reduction in OM in the 7-15 cm layer with the application of 10 and 20 m^3 ha^{-1} of biofertilizer can be attributed to the increase in the soil's microbiological activity, resulting in greater OM mineralization. Correia et al. (2011) evaluated the microbiological activity of the soil after the application of liquid swine manure (LSM) treated in an aerobic system, and found an increase of 533.34 µg g^{-1} of microbial biomass in the soil with LSM application equivalent to 500 kg nitrogen per ha.
Thus, the results obtained show that biofertilizer and cropping systems can improve the physical, chemical and biological characteristics of the soil.

Material and methods

Experimental location, area and design

The experiment was carried out at the Federal University of Northern Tocantins, Araguaína Campus, Brazil (7°5'43.74" South, 48°12'22.69" West and altitude of 259m), during the rainy season, from January to July. The region's climate is classified as AW - Tropical with humid summer (Koppen, 1948), well-defined dry and rainy seasons, and a dry period in the winter from June to September, with average annual temperature and rainfall of 25ºC and 1,746 mm, respectively.
The study was carried out on a typical Arctic Quartzarenic Neosol (according to the Brazilian soil classification). Before setting up the experiment, the area was sampled to check the chemical characteristics of the soil in the 0-15 cm layer. The soil had the following characteristics: 1.3 mg dm^{-3} of P; 2.4 mg dm^{-3} of K; 1.22 cmol dm^{-3} of Ca; 0.55 cmol dm^{-3} of Mg; 0.1 cmol dm^{-3} of Al; 1.93 cmol dm^{-3} of sum of bases (SB); 2.04 cmol dm^{-3} of CEC; 44.43% of the volume of saturation by bases (V); 1.5 g dm^{-3} of organic matter (OM) and pH in $CaCl_2$ of 4.17. One ton ha^{-1} of dolomitic limestone (PRNT >90%) was applied to correct the soil.
The experiment was carried out following the premises of a randomized block design, in split-plots, with five levels of biofertilizer (0; 10; 20; 30 and 40m^3 ha^{-1}) in the plots and two cropping systems (intercropping of sorghum with Piatã grass and monoculture of sorghum) in the subplots, totaling ten treatments in four replications, making up 40 plots of 10 m^2 (4 x 2.5m).
When the experiment was set up, the soil was slightly harrowed and fertilized with 30 kg.ha^{-1} of N (urea, single application), 30 kg ha^{-1} $year^{-1}$ of P (P_2O_5, single application) and 30 kg ha^{-1} $year^{-1}$ of K (K_2O, two applications). Fertilization was carried out in rows together with the sowing of Piatã grass and sorghum (BRS 610).
In the intercropping system, sorghum was sown in rows spaced 0.5 m apart and two additional rows of Piatã grass were sown between the sorghum rows. In the monoculture system, the sorghum was sown in rows using the same spacing as the intercropping system.
The biofertilizer was produced in three 1-m^3 barrels, using poultry litter from laying birds, with rice straw as the substrate. The ratio used was 1:3 (1 kg of litter to 3 kg of water), and the material remained in the barrels for 65 days. The levels of biofertilizer were applied at 25 and 44 days after seed germination, in rows close to the sowing row, using 10-L watering cans. The results of the chemical analysis of the biofertilizer are shown in Table 1.

Assessment of sorghum agronomic characteristics

The sorghum was evaluated at the end of the cycle, at the point of silage (dough grain with around 30% dry matter), 75 days after germination. The following agronomic and structural characteristics were assessed: stem diameter (mm), height (cm), leaf : stem ratio (L:S), number of plants (plants m^{-2}), green and dry mass yield (Mg ha^{-1}), proportion of stem, leaf, panicle and dead material in the dry mass (%), Brix, and Leaf Area Index (LAI). The plants in each plot were counted and ten representative plants were collected from each sampling unit, cutting tem at 10 cm from the ground. Next, the components leaf blade, stem plus sheath and dead material were separated from one sample and were packed in paper bags, identified and taken to a forced air circulation oven to dry at 55º C for 72 hours until it reached constant mass.

Evaluation of soil chemical attributes

At the end of the experimental period, soil samples were collected from the 0-7 cm and 7-15 cm layers. The chemical assessment of the soil included: Hydrogen potential (pH in $CaCl_2$), Phosphorus melich (P mg dm^{-3}), Potassium (K^+ mg dm^{-3}), Calcium (Ca^{2+} $cmol_c$ dm^{-3}), Magnesium (Mg^{2+} $cmol_c$ dm^{-3}), Aluminum (Al^{3+} $cmol_c$ dm^{-3}), sum of bases (SB $cmol_c$ dm^{-3}), effective cation exchange capacity (CECe $cmol_c$ dm^{-3}), aluminum saturation (m %) and organic matter (OM g dm^{-3}).

Statistical analysis

The variables analyzed were tested for normality (Kolmogorov-Smirnov test) and homoscedasticity (Cochran test) to check if the data was distributed normally and homogeneously. The variables that showed normality and homoscedasticity were analyzed through analysis of variance and the responses were subjected to regression analyses. The equation was chosen based on the coefficient of determination, and the significance of the regression and its coefficients were tested at the 5% probability level, as well as the biological significance of the response.

In order to verify the effects of the two cropping systems (monoculture of sorghum and intercropping of Piatã grass with sorghum) and the response of the treatments on the chemical characteristics of the soil, mean values were tested and compared by the Tukey's test at a 5% of significance level.

Conclusion

The use of biofertilizer obtained from the anaerobic bio-digestion of poultry litter compromises the performance of sorghum in intercropping but improves the production of green and dry mass in monoculture when used up to a level of 21.54 m^3 ha^{-1}. Higher levels impaired sorghum performance, suggesting the need to distribute the biofertilizer in greater numbers of applications during the production cycle to avoid negative effects.

The biofertilizer increased nutrient levels in the soil, but more research is needed to assess its long-term effectiveness and its persistence in the soil.

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Statement of contributions

The study was designed by OSJ and ACS, field work data were collected by OSJ, MODR and MODR. The first draft was written by OSJ and all authors commented on the discussion section. ICLS and JMLR review and edited. All authors read and approved the final version.

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