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Nitrogen sources on the chemical composition and productivity of maize alone and intercropped with brachiaria

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ABSTRACT: Maize-brachiaria intercropping has become adopted as a sustainable agricultural practice, capable of improving soil quality, optimizing nitrogen (N) use, and increasing the productive resilience of cropping systems. The objective of this study was to evaluate the effect of different N sources on the agronomic performance of maize. The experiment was conducted at Embrapa Agropecuária Oeste (Dourados, MS, Brazil). The experimental design was a randomized block design with a 2 × 4 factorial scheme, with three replications. The treatments included two maize cropping systems (monoculture and intercropped with brachiaria) and four N sources applied as topdressing: urea (45% N), urea with urease inhibitor (45% N), ammonium nitrate (27% N), and a control (no N). Plant height, biomass, grain yield, 100-grain weight, and nutrient content in the straw, and grains were evaluated. Maize monoculture showed greater accumulation of N and S in the grains, while maize-brachiaria intercropping increased C input in the straw and intensified nutrient cycling. N sources did not alter total biomass, but urea and urea with inhibitors increased N and Cu in the straw, and all increased N in the grains. It was concluded that intercropping combined with proper N management favors more sustainable systems for potential soil conservation.

Key words: competition, ammonium nitrate, urea, straw, nutrient uptake, nutrient export.

INTRODUCTION

Maize (*Zea mays* L.) is one of the most important grain crops in Brazil, with about 20 million hectares grown annually, generating approximately 85 million tons (Conab 2024). Its economic relevance and climate adaptability allow its cultivation in both spring-summer and autumn-winter (Ribeiro et al. 2024), either alone or intercropped with Brachiaria (sin. *Urochloa*). Results from corn-brachiaria intercropping and other combinations with grasses have stood out as a sustainable intensification strategy, especially in tropical regions like Brazil. Recent studies (Crusciol et al. 2020, Souza et al. 2024) indicate that, although there may be a slight reduction of 5 to 6% in corn productivity compared to monoculture, the intercropping system offers important benefits, such as greater soil conservation, increased vegetation cover, and residual biomass, favoring straw formation and the stability of the production system, in addition to improving nutrient use efficiency, especially nitrogen, through cycling promoted by grasses.

However, the magnitude of the results is highly dependent on local management and environmental factors, such as soil type, water regime, grass species used, seeding density, and fertilization strategies. This has been documented in recent meta-analyses and field studies that identify these factors as the main modulators of the variability in response of the maize-brachiaria intercropping system (Souza et al. 2024). Research conducted by the Brazilian Agricultural Research Corporation

(Embrapa) and Brazilian universities also reinforces that the success of the system requires regional adjustments in the choice of species, sowing time/method, and soil management, to avoid excessive competition between species and maximize the synergistic effects of the intercropping system.

Thus, the aim of this study was to evaluate the effect of nitrogen sources on productivity, phytotechnical characteristics, and nutrient levels of maize plants planted alone and intercropped with *Brachiaria* (sin. *Urochloa*).

MATERIAL AND METHODS

The work was carried out in the experimental area of Embrapa Agropecuária Oeste, located in the municipality of Dourados, MS, Brazil (Latitude 22°17'00"S, 54°49'00"W), in a Red Europhobic Latosol (Santos et al. 2018) (Table 1), with CwA climate, characterized by cold and dry winter and hot and humid summer (Fietz et al. 2017) (Fig. 1). The experiment was conducted in a 2 × 4 factorial scheme, with randomized block design, and three replicates. The first factor consisted of cropping systems (maize alone and maize intercropped with *brachiaria*), and the second factor comprised topdressing nitrogen sources: urea (45% N), ammonium nitrate (27% N), urea with urease inhibitor (45% N), and control (without N). Each plot measured 6 m × 6 m.

Table 1. Chemical characterization of soil in the experimental area. Dourados, MS, Brazil, 2023.

Water pH	Al^{3+}	Ca^{2+}	Mg^{2+}	$H^{+}+Al^{3+}$	K^{+}	SB	CEC (pH 7)
		$Cmol_c \cdot dm^{-3}$					
6.60	0.01	5.27	1.72	2.75	0.43	7.42	10.17
P (Mehlich^{-1})	**Cu^{2+}**	**Fe^{3+}**	**Mn^{2+}**	**Zn^{2+}**	**OM**	**C total**	**V**
$mg \cdot dm^{3}$					$g \cdot kg^{-1}$	%	
11.67	12.4	38.55	119.62	3.16	28.74	1.67	72.94

pH: hydrogen potential; Al^{3+}: aluminum; Ca^{2+}: calcium; Mg^{2+}: magnesium; $H^{+}Al^{3+}$: potential acidity; K+: potassium; SB: sum of exchangeable bases; CEC: effective cation exchange capacity; P: phosphorus; Cu: copper; Fe: iron; Mn: manganese; Zn: zinc; OM: organic matter; C: carbon; V: base saturation.

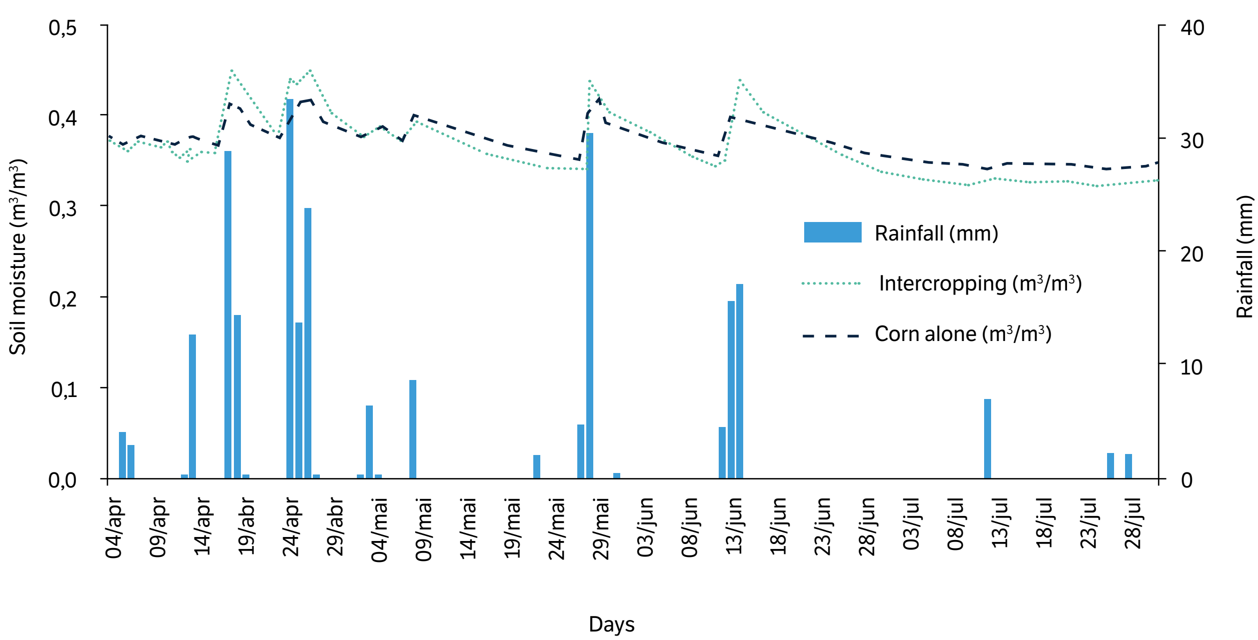

Figure 1. Rainfall (mm) and moisture (m³/m³) in soil under cultivation with corn alone and intercropped with brachiaria during the study period. Dourados, MS, Brazil, 2023.

The experimental area was organized in a block design. Each block contained eight plots: four dedicated to maize grown in monoculture, and four to maize intercropped with brachiaria. Within each cropping system, the four nitrogen sources were distributed among the plots. To minimize interference between treatments, a spacing of 50 cm was maintained between plots, while the distance between blocks was set at 15 m, ensuring adequate separation and reducing potential edge effects.

No-tillage sowing of maize and brachiaria was carried out on March 7, 2023, in succession to soybeans, using a row spacing of 50 cm, without chemical fertilization at sowing time. Brachiaria was sown simultaneously in the row as the maize using a specific seed compartment attached to the seeder. The K7500 VIP3 corn hybrid was chosen for its high productivity and good agronomic stability. Sowing was carried out aiming for a population of 60,000 plants per hectare. For the intercropping, *Brachiaria* was planted with a target population of 10,000 plants per hectare, following the methodology recommended by Ceccon et al. (2018). Atazine herbicide was applied at the dose of 1.5 $L{\cdot}ha^{-1}$ of i.a. at the V4 maize stage for invasive plant control, and this treatment was performed in all experimental plots. No herbicide was applied for brachiaria suppression.

Following the recommendations of Bulletin 100 (Raij et al. 1997) to ensure high productivity in the second crop after soybeans, 80 $kg{\cdot}ha^{-1}$ of N was manually applied as topdressing at the V5 stage of corn, a period recognized as one of the times of greatest nitrogen demand and absorption by the crop (Coelho and França 1995). Data regarding rainfall during the evaluation period were obtained at the Embrapa Agropecuária Oeste meteorological station located about 500 m from the experiment.

At harvest, plant height and ear insertion were evaluated. Top growth biomass was determined by collecting 10 corn plants from the central row and a 1 m^2 area for brachiaria. After collecting the ears, the weight of 100 grains was evaluated and productivity was estimated. The fresh biomass of both species was weighed and subsequently dried in an oven at 65°C until constant weight. Biomass and grain samples were sent to the laboratory for macro and micronutrient analysis, allowing quantification of nutrient extraction and export, according to the methodology of Machado (2005).

Statistical analyses were performed using the SISVAR software, version 5.8 (Ferreira 2019). The data were subjected to analysis of variance (ANOVA), and when significant, means were compared using the t-test and Tukey's test at a 5% probability level.

RESULTS AND DISCUSSION

The rainfall recorded during the experimental period was not sufficient to meet the water requirements for the full development of maize (Fig. 1). According to Machado (2016), maize requires between 400 and 600 mm of water throughout its cycle to achieve high yields. However, in the present study, the total accumulated precipitation was 357,8 mm, with the highest rainfall occurring between March and April (Fig. 1). Low rainfall causes water stress, leading to significant physiological changes (Sheoran et al. 2022), especially critical during pollination and grain filling phases. This water deficit reduces the photosynthetic rate (Bhat et al. 2020), limiting the production of photoassimilates and yield potential. Simultaneously, reduced water availability affects nitrogen dynamics in the soil-plant system (Hsiao and Xu 2020), decreasing mineralization and root absorption, which reduces nitrogen use efficiency. Thus, water stress combined with nutritional stress intensifies potential productivity losses (Ercoli et al. 2008).

According to the analysis of variance, there was a significant increased effect of the intercropping system on the maize biomass and total biomass (maize + brachiaria) (Table 2). A similar result was observed by Ceccon et al. (2013), who, after intercropping maize with brachiaria, found an increase in the post-harvest maize dry mass. A similar result was reported by Ceccon et al. (2013), who observed an increase in the dry mass of the corn after harvest when grown in intercropping with brachiaria. On the other hand, Crusciol et al. (2020) found that the export of N and S by the grains was higher in monoculture compared to intercropping, which is explained by the absence of competition for these nutrients in this system, allowing greater targeting of them to the grains.

Table 2. Plant height (PH), ear insertion (EI), maize biomass (CDM), corn + brachiaria biomass (CBDM), maize grain productivity (CGP), and brachiaria biomass (BDM) of maize alone and intercropped with brachiaria and topdressing nitrogen sources, in Dourados, MS, Brazil, 2023*.

Cultivation/N sources	PH	EI	CDM	CBDM	CGP	BDM
	------------- cm -------------		------------------------------------kg·ha^{-1} ------------------------------------			
Corn alone	215.0 a	101.2 a	7.453 b	7.453 b	7.162 a	0.000
Intercropped	214.8 a	103.2 a	9.598 a	12.775 a	6.759 a	3.145
Without N	210.3 a	102.5 a	7.948 a	9.818 a	6.347 a	3.8660 a
Ammonium nitrate	219.3 a	103.3 a	8.440 a	9.933 a	7.194 a	2.8230 b
Urea	215.8 a	98.6 a	8.370 a	10.068 a	7.241 a	3.297 ab
U+NBPT	214.1 a	104.3 a	9.345 a	10.298 a	7.059 a	2.5920 b
Mean	214.9	102.2	8.525	10.110	6.960	3.144
C.V. (%)	3.3	3.8	11.000	15.2	12.7	10.000

*Means followed by the same letter, in each variable, do not differ from each other neither by the t-test ($p < 0.05$) nor by the Tukey's test ($p < 0.05$) for cultivation systems and N sources, respectively; C.V.: coefficient of variation.

The results presented by Almeida et al. (2017a) and Almeida et al. (2017b), as well as those obtained in the present study, demonstrate that the intercropping of corn and brachiaria did not adversely biomass accumulate in corn. It was observed that maize biomass was higher when intercropped with brachiaria, as well as the total biomass (maize + brachiaria), which reached 9.598 and 12.775 kg·ha^{-1}, respectively, representing an increase of 28.8% (Table 2). These findings reinforced that maize-brachiaria intercropping is an efficient strategy for straw production and for improving the physical, chemical, and biological attributes of the soil, contributing to the sustainability of agricultural systems (Ceccon et al. 2013).

The analysis of variance indicated a significant effect of the cropping system on carbon (C) and copper (Cu) content in maize straw, as well as an effect of nitrogen sources on N and Cu content. However, the concentrations of N, P, K, Ca, Mg, S, Fe, Mn, Zn, and B in the straw were not influenced by the cropping systems (Table 3).

The lower concentration of N observed in intercropped corn grains can be attributed, in the first instance, to direct competition between the species for the fraction of N available in the soil, since both corn and brachiaria species have high N demands during the initial growth and forage formation cycle (Makino et al. 2019, Souza et al. 2024). However, a simple reduction in leaf or straw concentration does not necessarily imply yield loss: compensatory mechanisms, such as changes in biomass partitioning (dilution effect), greater efficiency in N use by the grain crop, and phenological adjustments, can maintain grain productivity. Meta-analyses and field studies show that, under proper management (density, sowing time, and fertilization), corn-brachiaria intercropping often presents neutral or similar grain productivity to monoculture, despite differences in leaf content (Souza et al. 2024).

In addition, intercropped maize plants did not show a reduction in grain productivity compared to monoculture and stood out for their higher P content (Table 4). These results are consistent with the findings of Makino et al. (2019), Seibert and Borsoi (2020), and Bovino et al. (2022)[1], who also reported that intercropping with brachiaria does not compromise grain productivity. During the experimental period, reduced precipitation levels likely limited both plant growth and the microbiological processes that control nitrogen transformation in the soil, affecting nutrient transport and absorption. However, the corn-brachiaria intercropping system can partially mitigate these effects through physical and biological mechanisms: the greater soil cover and straw produced by the brachiaria reduce water losses through evaporation and moderate the microclimate in the planting row, favoring the maintenance of surface moisture; simultaneously, the dynamics of residues and decomposition can release N at times less coincident with the peak demand of corn, reducing direct competition for N in the critical phase (Brito and Ferreira 2020, Ceccon et al. 2021) compared to monoculture.

1 Bovino, W. E. G., Gai, V. F. and Piovesan, G. (2022). Produtividade do milho no consórcio com braquiária. Annals of the 2º City Farm Fag, 165-174. Available at: https://themaetscientia.fag.edu.br/index.php/cityfarm/article/view/1686. Accessed on: Jan. 22, 2026.

Table 3. Nitrogen (N), carbon (C), phosphorus (P), potassium (K), magnesium (Mg), sulfur (S), calcium (Ca), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), and boron (B) contents in corn straw in sole and intercropped corn-brachiaria systems under different topdressing nitrogen sources, in Dourados, MS, Brazil, 2023*.

Cultivation/N sources	N	C	P	K	Mg	S
	----------%---------		---------------------------- g·kg^{-1} -------------------------			
Corn alone	1.04 a	42.37 b	0.64 a	12.03 a	2.32 a	0.94 a
Intercropped	0.88 a	42.70 a	0.57 a	11.03 a	2.39 a	0.79 a
Without N	0.69 b	42.32 a	0.50 a	10.63 a	2.19 a	0.74 a
Ammonium nitrate	0.92 ab	42.74 a	0.59 a	11.40 a	2.30 a	0.92 a
Urea	1.06 a	72.52 a	0.64 a	12.14 a	2.58 a	0.92 a
U+NBPT	1.17 a	42.56 a	0.71 a	11.95 a	2.36 a	0.89 a
Mean	0.96	42.53	0.61	11.53	2.35	0.87
C.V. (%)	19.50	0.80	27.0	18.70	13.40	20.5
Cultivation/N sources	**Ca**	**Cu**	**Fe**	**Mn**	**Zn**	**B**
	g·kg^{-1}	---------------------------------- mg·kg^{-1}--------------------------------				
Corn alone	3.55 a	6.27 a	405.99 a	75.24 a	14.00 a	7.07 a
Intercropped	3.33 a	5.17 b	342.51 a	73.73 a	11.97 a	6.47 a
Without N	3.64 a	4.37 b	340.43 a	77.83 a	12.11 a	6.32 a
Ammonium nitrate	3.34 a	5.89 ab	358.80 a	77.12 a	11.36 a	6.61 a
Urea	3.56 a	6.66 a	402.89 a	76.25 a	14.71 a	7.33 a
U+NBPT	3.22 a	5.95 a	394.88 a	66.75 a	13.76 a	6.82 a
Mean	3.44	5.72	374.25	74.48	12.99	6.77
C.V. (%)	18.00	16.40	28.6	22.3	22.10	17.80

*Means followed by the same letter, in each variable, do not differ from each other neither by the t-test ($p < 0.05$) nor by the Tukey's test ($p < 0.05$) for cultivation systems and N sources, respectively; C.V.: coefficient of variation.

Table 4. Nitrogen (N), carbon (C), phosphorus (P), potassium (K), magnesium (Mg), sulfur (S), calcium (Ca), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), and boron (B) contents in corn grains of corn planted alone and intercropped with brachiaria and topdressing nitrogen sources, Dourados, MS, Brazil, 2023.

Cultivation/N sources	N	C	P	K	Mg	S
	----------%---------		---------------------------- g·kg^{-1} -------------------------			
Corn alone	1.27 a	42.01 a	1.85 b	4.68 a	0.89 a	0.92 a
Intercropped	1.18 b	42.05 a	2.03 a	4.80 a	0.97 a	0.82 b
Without N	1.13 b	42.08 a	1.91 a	4.71 a	0.91 a	0.83 a
Ammonium nitrate	1.27 a	42.06 a	1.96 a	4.79 a	0.95 a	0.90 a
Urea	1.27 a	41.82 a	1.96 a	4.72 a	0.94 a	0.89 a
U+NBPT	1.24 a	42.16 a	1.91 a	4.74 a	0.95 a	0.88 a
Mean	1.23	42.03	1.94	4.74	0.93	0.87
C.V. (%)	4.70	1.0	8.60	4.60	10.8	6.00
Cultivation/N sources	**Ca**	**Cu**	**Fe**	**Mn**	**Zn**	**B**
	g·kg^{-1}	---------------------------------- mg·kg^{-1}--------------------------------				
Corn alone	0.05 a	1.22 a	106.55 a	5.04 a	16.25 a	0.93 a
Intercropped	0.02 a	1.25 a	71.34 a	5.42 a	16.86 a	0.87 a
Without N	0.01 a	1.25 a	68.25 a	5.24 a	17.13 a	0.84 a
Ammonium nitrate	0.02 a	1.20 a	90.51 a	5.41 a	16.00 a	0.95 a
Urea	0.09 a	1.21 a	111.27 a	5.26 a	17.06 a	0.91 a
U+NBPT	0.02 a	1.26 a	85.77 a	5.03 a	16.03 a	0.89 a
Mean	0.03	1.23	88.95	5.23	16.55	0.90
C.V. (%)	210.4	21.10	72.90	13.60	14.20	20.70

*Means followed by the same letter, in each variable, do not differ from each other neither by the t-test ($p < 0.05$) nor by the Tukey's test ($p < 0.05$) for cultivation systems and N sources, respectively; C.V.: coefficient of variation.

Effects on nutrients

Nitrogen

The nitrogen (N) content in corn straw showed a tendency to increase in treatments with urea, especially when associated with urease inhibitors, which exhibited the highest average values, followed by conventional urea. However, these differences were not statistically significant, with both treatments being similar to ammonium nitrate and control (Table 3). The observed effect can be explained by the fact that NBPT delays urea hydrolysis, reducing NH3 volatilization and increasing N availability in the soil. Fertilizers with NBPT can reduce these losses by up to 70–80% (Matse et al. 2024), increasing the N accessible to plants. In corn, this technology increases the absorption and efficiency of N use compared to conventional urea (Liu et al. 2020).

The residual effect of the more gradual N release, which can last from three to 14 days, was not observed during the autumn–winter season, likely due to low soil moisture, which limits enzymatic activity and N availability. According to Ni and Pacholski (2022), urea hydrolysis, diffusion of NH_4^+ and NH_3, and microbial N transformations depend on soil water, and under low moisture these processes slow down, reducing N release and availability. A similar pattern under water deficit was reported by Allende-Montalbán et al. (2021), who highlighted the moisture dependence of urease inhibitor efficiency.

Even with lower biomass, monoculture maize showed higher grain N content than intercropped maize, explained by greater internal N remobilization in monoculture and by the dilution effect associated with increased biomass in intercropping (Momesso et al. 2022). Reduced water availability also increases interspecific root competition and limits N uptake during grain filling, making intercropping more vulnerable to reduced N acquisition under stress (Silva et al. 2020). Although intercropping enhances N cycling and total system N, the mineralization of recycled N may not coincide with maize demand and can even result in losses, leading to neutral or negative effects on grain N content (Momesso et al. 2022).

There was no significant interaction between cropping systems and N sources, indicating that the sources behaved similarly in both systems. Table 4 shows that there was also no significant difference between N sources regarding grain productivity, reinforcing this homogeneity of response. Among the sources, nitrate showed lower N content in the grains compared to urea treated with a urease inhibitor, possibly due to its greater susceptibility to leaching in the soil profile (Wang et al. 2025). On the other hand, urea treated with urease inhibitors reduces losses due to NH_3 volatilization, increases N recovery by the crop, and tends to increase the N content in the grains compared to untreated urea (Castro et al. 2024). Recent studies also show that the relative effect of N sources remains consistent between different cropping systems when soil and water management is similar (Zhang et al. 2024).

Micronutrients and other elements

Copper (Cu) concentration in the straw remained within the sufficiency range for maize (4.18–19.79 $mg \cdot kg^{-1}$), ensuring adequate physiological functioning of the crop. Although maize in monoculture showed slightly higher values than in the intercropping system, this difference is probably not biologically relevant and may only be related to expected variations in cropping systems under competition for resources (Dimande et al. 2024).

In general, Table 4 indicates that neither the cropping system nor the nitrogen sources significantly altered most micronutrients, and trends observed for Cu (and possibly Zn) remained within adequate levels for the crop, without relevant agronomic impact. Studies corroborate that intercropping can modify nutrient dynamics in the soil, but without necessarily compromising the availability of micronutrients to plants (Moreira et al. 2019, Nasar et al. 2024).

Nutrient extraction and export

Among the cropping systems, differences were observed in the total extraction of carbon (C), potassium (K), and magnesium (Mg), with intercropped maize showing higher values (4.099, 106.2, and 22.9 kg·ha^{-1}, respectively) (Table 5). This trend corroborates results from recent studies indicating that maize-Brachiaria intercropping increases total biomass and, consequently, nutrient extraction, especially mobile elements such as K and Mg (Canisares et al. 2021, Silva et al. 2024).

Table 5. Extraction of macronutrients: nitrogen (N), carbon (C), phosphorus (P), potassium (K), magnesium (Mg), sulfur (S), calcium (Ca), and micronutrients: copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), and boron (B) — in straw (stem + leaves) of corn alone and intercropped with brachiaria and topdressing nitrogen sources, Dourados, MS, Brazil, 2023*.

Cultivation/N sources	N	P	K	Ca	Mg	S
	------------------------------ kg·ha^{-1} ------------------------------					
Corn alone	77.39 a	4.88 a	89.20 b	26.61 a	17.40 b	7.05 a
Intercropped	84.50 a	5.54 a	106.26 a	32.15 a	22.96 a	7.65 a
Without N	54.00 c	4.04 a	84.89 a	28.99 a	17.40 a	5.80 a
Ammonium nitrate	78.55 b	4.92 a	95.47 a	28.20 a	19.54 a	7.75 a
Urea	85.51 ab	5.21 a	99.62 a	29.91 a	21.59 a	7.51 a
U+NBPT	107.62 a	6.68 a	110.93 a	30.44 a	22.19 a	8.33 a
Mean	81.42	5.21	97.73	29.38	20.18	7.35
CV (%)	17.40	33.20	18.00	24.10	18.70	22.90
Cultivation/N sources	**Ca**	**Cu**	**Fe**	**Mn**	**Zn**	**B**
	----------kg·ha^{-1}----------		------------------------------ g·ha^{-1} ------------------------------			
Corn alone	3.157 b	47.43 a	3.020 a	565.13 a	105.26 a	53.37 a
Intercropped	4.099 a	50.33 a	3.295 a	716.81 a	115.38 a	62.43 a
Without N	3.363 a	35.33 a	2.739 a	623.77 a	96.82 a	50.99 a
Ammonium nitrate	3.607 a	48.83 a	2.939 a	651.61 a	95.14 a	54.77 a
Urea	3.561 a	55.59 a	3.308 a	648.82 a	122.13 a	61.71 a
U+NBPT	3.981 a	55.77 a	3.644 a	639.68 a	127.20 a	64.13 a
Mean	3.628	48.88	3.157	640.97	110.32	57.90
C.V. (%)	11.700	25.3	30.3	29.5	27.3	25.6

*Means followed by the same letter, in each variable, do not differ from each other neither by the t-test ($p < 0.05$) nor by the Tukey's test ($p < 0.05$) for cultivation systems and N sources, respectively; C.V.: coefficient of variation.

Regarding nitrogen sources, urea treated with a urease inhibitor (NBPT) showed greater N uptake by plants compared to nitrate and the control, without differing from conventional urea. Although the present study did not directly assess ammonia volatilization losses, the results are consistent with the literature, which indicates that the use of NBPT tends to reduce NH3 volatilization and improve synchronization between N release and crop demand, thereby increasing nutrient use efficiency (Ahmed et al. 2023, Szulc et al. 2023).

Regarding nutrient exports by grains, monoculture maize showed higher exports of N (91 kg·ha^{-1}) and S (6.61 kg·ha^{-1}) than intercropped maize (79.8 and 5.62 kg·ha^{-1}, respectively) (Tables 4 and 6). This difference may be related to the synergistic interaction between N and S, whereby greater N availability favors S uptake and translocation, promoting higher accumulation of proteins and sulfur-containing compounds in the grains (Agyin-Birikorang et al. 2024). Thus, although intercropping may intense nutrient cycling in the soil-plant system, monoculture tends to present greater N and S export due to reduced root competition and greater availability of assimilable N in the soil profile.

Table 6. Exportation of chemical elements — nitrogen (N), carbon (C), phosphorus (P), potassium (K), magnesium (Mg), sulfur (S), calcium (Ca), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), and boron (B) — by corn grains planted alone and intercropped with brachiaria with topdressing nitrogen sources, Dourados, MS, Brazil, 2023*.

Cultivation/N sources	N	P	K	Ca	Mg	S
	kg·ha^{-1}					
Corn alone	91.00 a	3.008 a	13.20 a	33.46 a	6.38 a	6.61 a
Intercropped	79.80 b	2.842 a	13.74 a	32.48 a	6.56 a	5.62 b
Without N	72.23 a	2.671 a	12.12 a	29.86 a	5.74 a	5.24 b
Ammonium nitrate	91.74 a	3.025 a	14.15 a	34.39 a	6.88 a	6.49 a
Urea	92.05 a	3.028 a	14.21 a	34.23 a	6.79 a	6.49 a
U+NBPT	88.24 a	2.975 a	13.41 a	33.41 a	6.47 a	6.25 ab
Mean	86.06	2.925	13.47	32.97	6.47	6.12
C.V. (%)	13.9	12.5	13.26	11.4	12.11	13.14
Cultivation/N sources	**Ca**	**Cu**	**Fe**	**Mn**	**Zn**	**B**
	kg·ha^{-1}		g·ha^{-1}			
Corn alone	0.15 a	8.69 a	764.96 a	36.08 a	116.11 a	6.67 a
Intercropped	0.17 a	8.43 a	464.04 a	36.63 a	113.30 a	5.93 a
Without N	0.10 a	7.77 a	440.00 a	32.78 a	106.72 a	5.32 a
Ammonium nitrate	0.14 a	8.55 a	670.84 a	38.97 a	113.76 a	6.79 a
Urea	0.74 a	8.89 a	785.58 a	37.99 a	124.99 a	6.64 a
U+NBPT	0.20 a	9.03 a	621.56 a	35.69 a	113.35 a	6.43 a
Mean	0.16	8.56	629.50	114.7	114.71	6.3
C.V. (%)	81.7	23.0	77.2	21.1	21.1	23.0

*Means followed by the same letter, in each variable, do not differ from each other neither by the t-test ($p < 0.05$) nor by the Tukey's test ($p < 0.05$) for cultivation systems and N sources, respectively; C.V.: coefficient of variation.

CONCLUSION

The maize-brachiaria intercropping system is a sustainable ecological intensification strategy that produces more biomass for soil protection, increasing total biomass, and straw contributions to the soil. Although intercropping resulted in a slight competition for N and water, overall, the maize intercrop maintained an adequate nutritional performance. The system efficiency was enhanced by using controlled-release N sources, which may improve the nitrogen use efficiency and reduce losses due to leaching and volatilization.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Methodology: Oliveira, T. C. C.; **Formal Analysis:** Oliveira, T. C. C. and Ceccon, G.; **Investigation:** Oliveira, T. C. C.; **Writing – Original Draft:** Oliveira, T. C. C. and Ceccon, G.; **Project administration:** Ceccon, G., Tomazi, M. and Bayer, C.; **Writing – Review and Editing:** Ceccon, G., Tomazi, M. and Bayer, C. **Resources:** Ceccon, G., Tomazi, M. and Bayer. C.; **Final approval:** Oliveira, T. C. C.

DATA AVAILABILITY STATEMENT

All data supporting the findings of this study are included within the article.

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DECLARATION OF USE OF ARTIFICIAL INTELLIGENCE TOOLS

The authors declare that no artificial intelligence tools were used in the preparation of this manuscript.

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