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Original Article

Yield of maize in an intercropping system with peanut under nitrogen fertilization

Produtividade do milho em sistema consorciado com amendoim sob adubação nitrogenada

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Abstract

Nitrogen fertilization can significantly enhance the productivity of maize and peanuts in an intercropping system. This study aimed to evaluate the impact of full, partial, or complementary substitution of nitrogen fertilization through intercropping with peanuts on leaf nutrient levels and maize yield. The experiment was conducted from February to May 2021, at an area belonging to the Universidade da Integração Internacional da Lusofonia Afro-Brasileira (UNILAB) in Redenção, Ceará state (Brazil). The experimental design was a randomized block design with five treatments: MP0 (maize intercropped with peanuts without nitrogen fertilization), MP50 (maize intercropped with peanuts with 50% of the recommended nitrogen dose), MP100 (maize intercropped with peanuts with 100% of the recommended nitrogen dose), MN50 (maize in monoculture with 50% of the recommended nitrogen dose), and MN100 (maize in monoculture with 100% of the recommended nitrogen dose), each with four replications. The results indicate that intercropping maize with peanuts improves the efficiency of nitrogen fertilization and land use. However, complete substitution of nitrogen fertilization in the maize-peanut intercropping system is not recommended due to the observed lower growth and yield indices.

Keywords: *Zea mays*, *Arachis hypogaea*, nitrogen use efficiency, plant nutrition.

Resumo

A adubação nitrogenada pode aumentar significativamente a produtividade do milho e do amendoim em um sistema consorciado. Este estudo teve como objetivo avaliar o impacto da substituição total, parcial ou complementar da adubação nitrogenada por meio do consórcio com amendoim nos níveis de nutrientes nas folhas e na produtividade do milho. O experimento foi conduzido de fevereiro a maio de 2021, em uma área pertencente à Universidade da Integração Internacional da Lusofonia Afro-Brasileira (UNILAB) em Redenção, estado do Ceará (Brasil). O delineamento experimental foi em blocos ao acaso com cinco tratamentos: MP0 (milho consorciado com amendoim sem adubação nitrogenada), MP50 (milho consorciado com amendoim com 50% da dose recomendada de nitrogênio), MP100 (milho consorciado com amendoim com 100% da dose recomendada de nitrogênio), MN50 (milho em monocultura com 50% da dose recomendada de nitrogênio) e MN100 (milho em monocultura com 100% da dose recomendada de nitrogênio), cada um com quatro repetições. Os resultados indicam que o consórcio de milho com amendoim melhora a eficiência da adubação nitrogenada e o uso da terra. No entanto, a substituição completa da adubação nitrogenada no sistema consorciado milho-amendoim não é recomendada devido aos menores índices de crescimento e produtividade observados.

Palavras-chaves: *Zea mays*, *Arachis hypogaea*, eficiência do uso do nitrogênio, nutrição de plantas.

1. Introduction

Maize (*Zea mays* L.) is one of the most important agricultural crops globally, ranking among the top three most widely cultivated cereals (Coêlho, 2024). In Brazil, maize plays a strategic role in agribusiness, making a substantial contribution to the country's agricultural economy (CONAB, 2024). The successful production of maize is highly dependent on effective management practices, particularly fertilization, with nitrogen (N)

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being a key nutrient (Asibi et al., 2019). Nitrogen is the most critical nutrient for maize, as it directly impacts essential physiological processes such as photosynthesis and protein synthesis, both of which are vital for the crop's development and production quality (Simão et al., 2017; Taiz et al., 2017).

Although most nitrogen is present in the atmosphere rather than in the soil (Prado, 2020) nitrogen fertilization is essential to meet the demands of nitrogen-intensive crops like grasses, which adds significant costs for producers (Silva et al., 2024). Adopting technologies that increase soil nitrogen availability and reduce the need for synthetic nitrogen fertilizers in maize cultivation is crucial for maximizing productivity while minimizing production costs. Consequently, strategies that improve nitrogen use efficiency, such as crop rotation and intercropping with legumes, are gaining increasing importance (Zhao et al., 2024; Mupangwa et al., 2021).

Intercropping maize with legumes, such as peanuts (*Arachis hypogaea* L.), represents one of these promising strategies, as the efficient utilization of resources in intercropped systems can result in higher production compared to monocultures (Li et al., 2019). Legumes possess the unique ability to fix atmospheric nitrogen through a symbiotic relationship with bacteria of the Rhizobium genus, converting atmospheric N2 into forms that are assimilable by plants (Mohammadi et al., 2012). This biological nitrogen fixation (BNF) is a crucial process that benefits not only the legume but also the intercropped crops, such as maize, by improving soil fertility and reducing the need for synthetic nitrogen fertilizers (Li et al., 2022).

Studies indicate that intercropping legumes with cereals results in highly productive ecosystems (Tian et al., 2021; Du et al., 2020; Nurgi et al., 2023). In addition, intercropping legumes with cereals have significant impacts on soil health and the long-term sustainability of agricultural systems. The presence of legumes enhances the soil's microbial structure, increasing its biodiversity and its capacity for water and nutrient retention (Fu et al., 2019). These factors contribute to the resilience of agricultural systems, making them less vulnerable to abiotic stresses and promoting long-term sustainability (Dong et al., 2022). The reduction in the need for synthetic fertilizers and the increase in soil organic matter are also important aspects that reinforce the viability of intercropping as a sustainable agricultural practice (Soumare et al., 2020).

Peanut stands out among legumes due to its high nitrogen-fixing capacity, rapid initial growth, lower water and fertilizer requirements compared to corn, and its status as a high-value crop and protein source, making it an ideal choice for intercropping with maize (Feng et al., 2021). In addition to providing nitrogen to the system, peanut residues are rich in organic matter, which contributes to the improvement of soil structure and the availability of nutrients for subsequent crops (Shen et al., 2019).

Thus, the objective was to evaluate the effect of complete, partial, or complementary substitution of nitrogen fertilization by peanut intercropping on the foliar contents and production of maize.

2. Material and Methods

2.1. Location and characterization of the experimental area

The experiment was conducted from February to May 2021, during the rainy season, under field conditions at the experimental area of the Universidade da Integração Internacional da Lusofonia Afro-Brasileira (UNILAB) in Redenção, Ceará, Brazil. The site is located at 4º13'33" S latitude, 38°43'50" W longitude, and an altitude of 88.8 meters.

The region's climate is classified as BSh' (semi-arid tropical), characterized by very high temperatures, a rainy season from February to May, intense solar radiation, and high evaporation rates (Alvares et al., 2013). During the experiment, daily records of rainfall, as well as maximum and minimum air temperatures, were collected using a HOBO® U12-012 Temp/RH/Light/Ext data logger (Figure 1).

The soil in the area is classified as an Ultisol with a sandy loam texture. The chemical characteristics of the soil were determined by collecting simple subsamples from the 0 to 0.20 m layer of the experimental area, which were analyzed according to the methodology described by (Teixeira et al., 2017). The chemical characteristics analyzed are presented in Table 1.

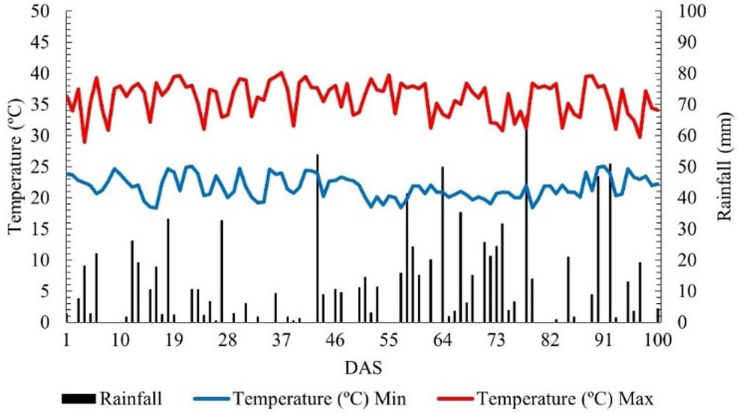

Figure 1. Mean values for maximum (Max) and minimum (Min) temperatures and precipitation were obtained during the experimental cycle.

Table 1. Chemical characteristics of the soil sample before applying the treatments.

OM	N	P	K^+	Ca^{2+}	Mg^{2+}	Na^+	H^++Al^{3+}	Al^{3+}	C/N	pH	V
(g dm^3)		(mg dm^3)	($cmol_c$ dm^3)							(H_2O)	(%)
8.79	0.53	73.00	0.11	6.30	1.60	0.59	1.32	0.05	10.00	7.60	87.00

OM: Organic matter; P: assimilable phosphorus, extractor Mehlich 1; V: Base saturation.

2.2. Experimental design and treatments

The experimental design adopted was a randomized block design corresponding to five fertilization strategies in maize crop (MP0 = maize intercropping system with peanut without nitrogen fertilization - N; MP50 = maize intercropping system with peanut with 50% of the recommended N dose; MP100 = maize intercropping system with peanut with 100% of the recommended N dose; MN50 = monoculture maize with 50% of the recommended N dose; and MN100 = monoculture maize with 100% of the recommended N dose) with four replications.

2.3. Monoculture and intercropping production systems

The area was initially cleared and prepared. Maize was planted at the beginning of the rainy season (January), and peanuts were sown in the intercropping treatments 15 days later.

The maize hybrid used was AG 1051 (*Zea mays* L.), characterized by its dual-purpose nature for grain production and fodder, with a semi-early cycle and a dent maize type. For peanut (*Arachis hypogaea* L.), the commercial variety BR-1, developed by the Brazilian Agricultural Research Corporation (EMBRAPA), was used without inoculation. This variety is described as having an erect growth habit, medium-sized pods, and an early cycle.

Cultivation was arranged in rows with planting in holes, comprising a total of six rows, each 14 meters long, spaced 1 meter apart, and with 0.20 meters between plants. The two outer rows included a 1-meter spacing at each end and 0.50 meters between plots for border areas. In the intercropping treatments, peanuts were planted 15 days after maize, parallel to and 0.10 meters from the maize rows. Each plot had a usable area of 2 m^2, resulting in a total usable area of 40 m^2. Weeds were controlled through periodic manual weeding, and pest control was managed with a Bacillus thuringiensis-based insecticide as needed.

2.4. Fertilization management (NPK)

Fertilization followed the recommendations of (Ribeiro et al., 1999). Phosphorus (P) and potassium (K) fertilization involved applying 100 kg ha^{-1} of P and 80 kg ha^{-1} of K using single superphosphate (18% P_2O_5) and potassium chloride (60% K_2O), respectively. These fertilizers were applied in two stages: the first at planting and the second at 21 days after sowing (DAS), incorporated into furrows 10 cm deep. Additionally, zinc was applied by fertigation at a rate of 2 kg ha^{-1} using zinc sulfate (21% Zn).

2.5. Irrigation management

Irrigation depths were determined based on evapotranspiration (ETo) values estimated using the Class A Pan method and crop coefficients (Kc) recommended for different phenological stages of crops (Doorenbos and Kassam, 1994). Crop evapotranspiration, in mm day-^{1}, was calculated using Equation 1.

$$ETc = ECA \times Kp \times Kc \qquad \text{Equation 1}$$

where:
ETc – Crop evapotranspiration, in mm day^{-1};
ECA - Evaporation measured in the class A pan, in mm/day^{-1};
Kp - Class A pan coefficient, dimensionless; and
Kc - Crop coefficient, dimensionless.

The irrigation time was obtained using Equation 2:

$$It = \frac{ETc \times Ep}{Ea \times q} \times 60 \qquad \text{Equation 2}$$

where:
It - Irrigation time (min);
ETc - Crop evapotranspiration for the period (mm);
Sd - Spacing between emitters;
Af - Application efficiency (0.92); and
q - Flow rate (8 L h^{-1}).

2.6. Variables under analysis

2.6.1. Maize biomass production

At 100 DAS, the aerial parts of five plants for treatment were harvested and separated into different components (leaves and stems). These were dried in a forced-air oven at 65°C until a constant weight (72 hours). After this period, the dry mass of the leaf (LDM) and stems (SDM) was determined using an analytical balance.

2.6.2. Concentration of mineral elements in the leaves of maize

Samples were dried and then ground using a Wiley-type mill. Nitrogen (N) concentration was determined by the Kjeldahl method (Miyazawa et al., 2009), which includes wet digestion, steam distillation, and titration to quantify NH^{4+}. Phosphorus, K, Mg, Ca were determined by dry digestion in a muffle furnace using a 1% HNO3 solution as an extractant. A 500 mg sample of leaf tissue was placed in an electric muffle furnace and incinerated at temperatures between 500 and 550 °C. The resulting ash was dissolved in nitric acid and the extract obtained was used for the determination of P, K, Mg and Ca. Potassium (K) was measured by flame photometry, phosphorus (P) by molybdenum blue spectrophotometry, and magnesium (Mg) and calcium (Ca) by atomic absorption spectrophotometry (Silva, 2009).

2.6.3. Yield of maize

Yield characteristics were determined as follows: ear length (EL) and diameter (ED) were measured using a ruler (cm) and a digital caliper (mm) through the longitudinal and transverse measurements of the ears without straw, respectively; ear mass with straw (EMWS) and without straw (EMWoS) were measured by weighing the ears on an analytical balance; thousand-grain mass (TGM) was determined by weighing one thousand grains from each experimental plot on an analytical balance; and grain yield (Y) was estimated in kilograms per hectare (kg ha^{-1}) based on grain mass and plant density used per hectare (50,000 plants ha^{-1}).

2.6.4. Agronomic efficiency in nitrogen use by maize

The agronomic efficiency index of nitrogen in maize was calculated by (Fageria, 1998) following Equation 3:

$$AEN = \frac{YG_{WN} - YG_{WON}}{Q_{NA}} \quad \text{Equation 3}$$

where:
AEN - Agronomic Efficiency in Nitrogen Use;
YGWN – Yield grains with nitrogen fertilizer (kg ha^{-1});
YGWON - Yield grains without nitrogen fertilizer (kg ha^{-1}); and
QNA - Quantity of N applied (kg ha^{-1}).

2.6.5. Partial land equivalent ratio

To determine the maize yield in intercropping compared to monoculture, the partial land equivalent ratio (pLER) was calculated as the relative advantage of intercropping over monoculture as described by (Van der meer, 1989) according to Equation 4:

$$pLER = \frac{Y_I}{Y_M} \quad \text{Equation 4}$$

where:
pLER - Partial land equivalent ratio;
Y_I – Yield grains under intercropping (kg ha^{-1}); and
Y_M – Yield grains under monoculture (kg ha^{-1}).

2.7. Data analysis

The data obtained were subjected to the Kolmogorov-Smirnov normality test at the 0.05 probability level. After the normality test, analyses of variance were performed using the F-test ($p < 0.05$). In cases of statistical significance, the means were compared using the Tukey test ($p < 0.05$) with the Assistat 7.7 Beta software (Silva and Azevedo, 2016).

3. Results

3.1. Biomass production and concentration of mineral elements in the leaves

The analysis of variance presented in Table 2 shows that the dry masses of the stem and leaves, as well as foliar nitrogen and calcium contents, were significantly influenced by the fertilization strategies ($p \leq 0.01$). However, phosphorus, potassium and magnesium contents in maize leaves were not significantly affected.

Greater dry mass partitioning was observed in different parts of the maize plant under MP100, with 367.25 g plant^{-1} for stem dry mass (Figure 2A) and 99.00 g plant^{-1} for leaf dry mass (Figure 2B).

The MP100 treatment (maize intercropping with peanut combined with a 100% N dose) favored a greater uptake and assimilation of N (29.1 g kg^{-1}) in maize plants (Figure 2C). For leaf calcium concentrations (Figure 2D), the MP50 (maize/peanut intercropping with 50% N), MN50 (maize monoculture with 50% N), and MN100 (maize monoculture with 100% N) treatments showed statistically significant superiority compared to the other treatments.

3.2. Yield

The analysis of variance presented in Table 3 presented that all variables of production, ear length, and diameter, ear mass with, and without straw, thousand-grain mass, and yield were significantly influenced by the fertilization strategies ($p \leq 0.01$).

For ear length, the MP100 treatment (maize monoculture with 100% of the N dose) had the highest average at 22.73 cm, followed by the MP100 treatment (maize/peanut intercropping with 100% of the N dose) at 19.84 cm. The MP50 (maize/peanut intercropping with 50% of the recommended N) and MN50 (maize monoculture with 50% of the N dose) treatments showed similar results, with mean values of 16.75 cm and 16.79 cm, respectively. The MP0 treatment (maize/peanut intercropping without N) had the lowest average ear length at 15.38 cm (Figure 3A).

Table 2. Summary of the analysis of variance for stem dry mass (SDM), leaf dry mass (LDM), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) contents in maize leaves under different fertilization strategies.

SV	DF	Mean Square						
		SDM	LDM	N	P	K	Ca	Mg
Blocks	3	4148.53^{ns}	46,18^{ns}	2.21^{ns}	0.19^{ns}	1.92^{ns}	0.001^{ns}	0.0006^{ns}
Fertilization strategies	4	31043.37**	1327.25**	75.32**	0.70^{ns}	4.09^{ns}	0.016*	0.002^{ns}
Residual	12	3777.57	164.18	7.89	0.55	1.08	0.002	0.002
Mean	-	241.00	70.75	23.91	3.27	17.49	0.20	0.35
CV (%)	-	15.60	18.11	11.74	22.85	5.95	13.84	13.60

SV: Source of variation; DF: Degrees of freedom; CV: Coefficient of variation. ns, *, and **: not significant, significant at $p \leq 0.05$, and significant at $p \leq 0.01$, respectively.

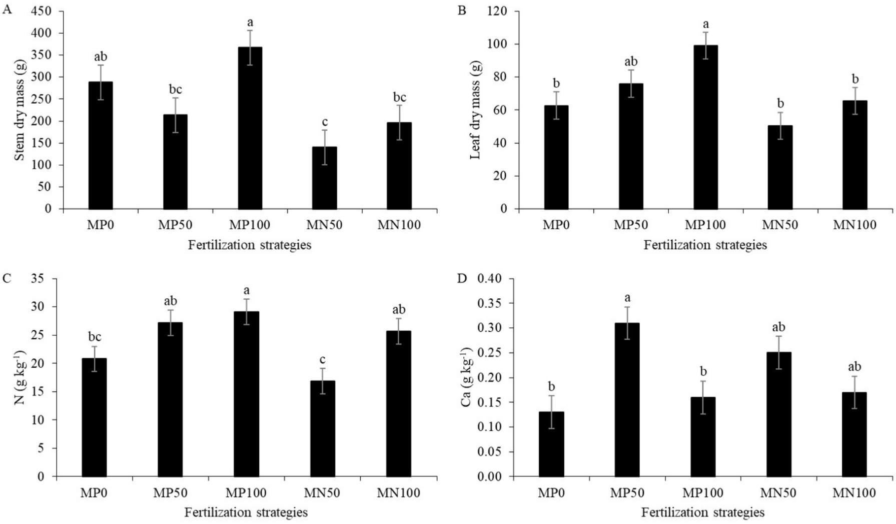

Figure 2. Stem dry mass (A), leaf dry mass (B), leaf concentrations of nitrogen (C) and leaf concentrations of calcium (D) of maize plants under different fertilization strategies. MP0 = maize intercropping system with peanut without nitrogen fertilization; MP50 = maize intercropping system with peanut with 50% of the N dose; MP100 = maize intercropping system with peanut with 100% of the N dose; MN50 = monoculture maize with 50% of the N dose; and MN100 = monoculture maize with 100% of the N dose. Lowercase letters compare means by Tukey test (p ≤ 0.05). Error bars represent the standard error of the mean (*n* = 4).

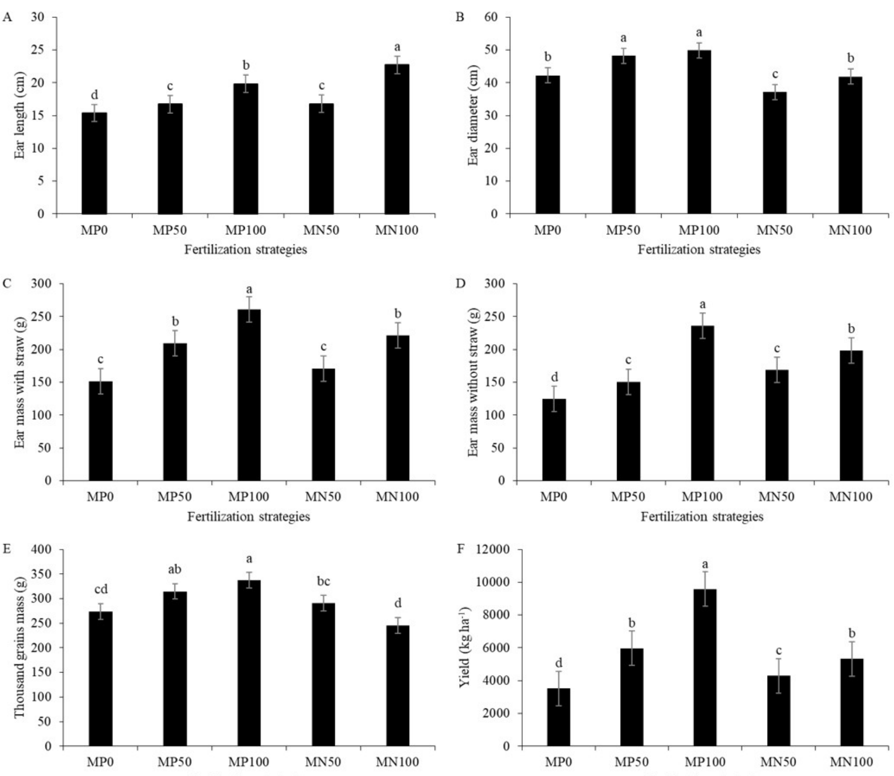

Figure 3. Ear Length (A), ear dimeter (B), ear mass with straw (C) ear mass without straw (D), thousand grain mass (E) and yield (F) of maize plants under different fertilization strategies. MP0 = maize intercropping system with peanut without nitrogen fertilization; MP50 = maize intercropping system with peanut with 50% of the N dose; MP100 = maize intercropping system with peanut with 100% of the N dose; MN50 = monoculture maize with 50% of the N dose; and MN100 = monoculture maize with 100% of the N dose. Lowercase letters compare means by Tukey test ($p \leq 0.05$). Error bars represent the standard error of the mean (*n* = 4).

For ear diameter (Figure 3B), MP100 and MP50 strategies produced the largest diameters that were not statistically different from each other, with average values of 49.86 mm and 48.24 mm, respectively.

The highest ear mass with straw was observed for the MP100 fertilization strategy, with an average value of 261.18 g. The MP50 and MN100 strategies presented values of 209.53 g and 221.08 g, respectively, with no significant difference between them. The lowest mean values for ear mass with straw were found for the MA0 and MN50 strategies (151.70 g and 171.11 g, respectively) (Figure 3C).

For ear mass without straw (Figure 3D), the MP100 fertilization strategy achieved the highest value at 236.33 g, followed by the MN100 strategy with an average of 198.09 g. The MP50 and MN50 strategies showed no significant difference, with averages of 150.88 g and 169.03 g, respectively. The MP0 strategy had the lowest ear mass without straw, averaging 124.81 g.

For the 1000-grain mass (Figure 3E), the MP50 and MP100 treatments exhibited higher mean values of 314.66 g and 337.33 g, respectively. In contrast, the MP0 and MN100 treatments showed lower values of 273.88 g and 245.66 g, respectively.

As shown in Figure 3F, the MP100 strategy achieved the highest yield at 9,580.55 kg ha^{-1}, followed by the MP50 and MN100 strategies with average yields of 5,962.77 kg ha^{-1} and 5,315.83 kg ha^{-1}, respectively. The MN50 strategy yielded an intermediate value of 4,294.13 kg ha^{-1}, while the MP0 strategy had the lowest yield at 3,513.33 kg ha^{-1}.

3.3. Agronomic efficiency in nitrogen use and partial land equivalent ratio

The agronomic efficiencies in nitrogen use and partial land use were significantly influenced by the fertilization strategies ($p \leq 0.01$) (Table 4).

The intercropping system (maize/peanut), regardless of the nitrogen dose (50% or 100%), provided greater agronomic efficiency in nitrogen use compared to maize monoculture under the same fertilization conditions (Figure 4A).

Table 3. Summary of the analysis of variance for ear length (EL), ear diameter (ED), ear mass with straw (EMWS), ear mass without straw (EMWoS), thousand grain mass (TGM), and yield (Y) in maize plants under fertilization strategies.

SV	DF	Mean Square					
		EL	ED	EMWS	EMWoS	TGM	Y
Blocks	3	0.16^{ns}	1.57^{ns}	102.00^{ns}	150.54^{ns}	193.36^{ns}	81680.19^{ns}
Fertilization strategies	4	35.24**	107.16**	7403.58**	7427.30**	5045.74**	22,027,760.50**
Residual	12	0.22	2.62	214.41	177.66	312.99	111273.94
Mean	-	18.29	43.86	202.92	175.83	292.37	5733.32
CV (%)	-	2.57	3.70	7.22	7.58	6.05	5.82

SV: Source of variation; DF: Degrees of freedom; CV: Coefficient of variation. ns, *, and **: not significant, significant at $p \leq 0.05$, and significant at $p \leq 0.01$, respectively.

Table 4. Summary of the analysis of variance for agronomic efficiency in nitrogen use (AEN) and partial land use efficiency (pLER) in maize plants under fertilization strategies.

SV	DF	Mean Square	
		AEN	pLER
Blocks	3	67.50^{ns}	0.009^{ns}
Fertilization strategies	4	2021.21**	1.27**
Residual	12	41.65	0.002
Mean	-	35.82	1.12
CV (%)	-	12.02	4.19

SV: Source of variation; DF: Degrees of freedom; CV: Coefficient of variation. ns, *, and **: not significant, significant at $p \leq 0.05$, and significant at $p \leq 0.01$, respectively.

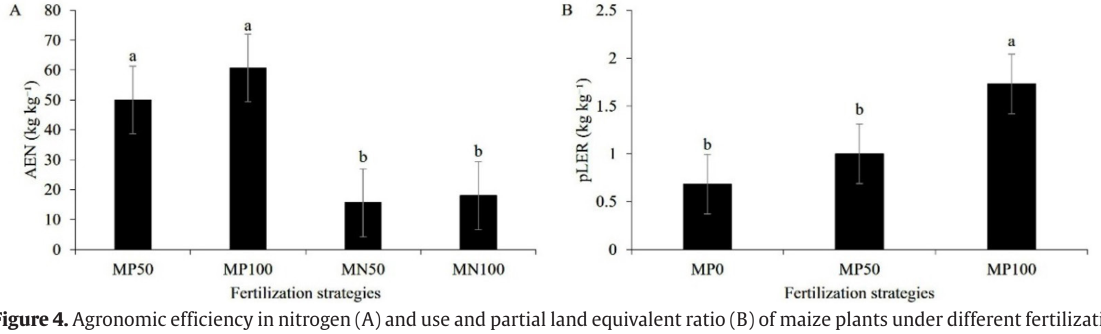

Figure 4. Agronomic efficiency in nitrogen (A) and use and partial land equivalent ratio (B) of maize plants under different fertilization strategies. MP0 = maize intercropping system with peanut without nitrogen fertilization; MP50 = maize intercropping system with peanut with 50% of the N dose; MP100 = maize intercropping system with peanut with 100% of the N dose; MN50 = monoculture maize with 50% of the N dose; and MN100 = monoculture maize with 100% of the N dose. Lowercase letters compare means by Tukey test ($p \leq 0.05$). Error bars represent the standard error of the mean ($n = 4$).

Partial land use efficiency was statistically superior under the MP100 treatment (maize intercropping with peanut at 100% N) compared to the other fertilization levels (MP0 and MP50) in the intercropping system (Figure 4B).

4. Discussion

4.1. Biomass production and concentration of mineral elements in the leaves

The superiority of the MP100 treatment may be attributed to factors such as the appropriate nitrogen dose for maize and the biological nitrogen fixation (BNF) by peanut, which may provide an additional source of this nutrient for maize. Furthermore, according to (Li et al., 2021), resource optimization in intercropping systems can increase biomass compared to monoculture situations.

A study by (Gao et al., 2022) on dry mass and nitrogen accumulation in maize/peanut intercropping systems confirmed the benefits of this approach, demonstrating that dry mass gains in maize are significantly enhanced with higher nitrogen doses. Similarly, (Qiu et al., 2023), evaluating cotton intercropping with different crops, observed an increase in aerial biomass (15.5%) and leaves (22%) compared to the monoculture system. These authors also emphasized that the cotton/peanut intercropping resulted in the highest biomass gains, demonstrating the positive effect of intercropping with legumes.

This is due to the competition of maize roots for nutrient uptake in the presence of peanut roots. These results highlight the potential of intercropping as an effective strategy to improve nitrogen nutrition. Similar results to the present study were found by (Dong et al., 2022), who observed superior N accumulation in maize plants intercropping with peanut. These authors suggest that competition in the intercropping system stimulates nitrogenase activity, which promotes greater fixation by peanut and subsequent N transfer to maize.

Although calcium is an immobile nutrient within the plant, the co-presence of a legume likely resulted in higher accumulation in the maize plants. A study detailing the effect of nutrient uptake in intercropping systems was described by (Makino et al., 2019). These authors also found higher leaf calcium concentrations in maize grown alone compared to maize intercropping system with Brachiaria.

4.2. Yield

The larger ear development observed in the 100% N dose treatment is attributed to the role of nitrogen in plant metabolism, as it directly affects photosynthesis, the composition of molecules such as amino acids and ATP, and promotes increased shoot growth and biomass accumulation, which is ultimately reflected in ear size (Taiz et al., 2017; Li et al., 2019).

The smallest mean ear diameter was observed with the MN50 treatment, with a mean of 37.12 mm. Similar results were reported by (Saldanha et al., 2017), who studied mineral fertilization and maize + legume (cowpea) intercropping and found positive effects on both ear length and diameter.

These results suggest a beneficial effect of intercropping with peanut, which probably improves nitrogen fertilizer efficiency either by minimizing losses or by increasing soil assimilation. (Fu et al., 2019) confirmed these findings by demonstrating that intercropping systems increased crop productivity and resource use. Contrary results were found by (Sousa et al., 2022) who, while investigating nitrogen doses in monoculture system of maize, recorded the highest ear mass with straw at 50% dose. However, this was not statistically different from the recommended 100% nitrogen dose.

Contrary to the results of this study, (Carmo et al., 2020), who studied the productive performance of maize with different nitrogen doses, found no significant difference in ear mass between the 0% and 100% N doses. Similarly, (Sousa et al., 2022) found no statistical difference for this variable between the 100% and 50% N doses.

These findings contrast with those of (Nurgi et al., 2023), who, in a study on different intercropping densities between maize and fava beans, reported higher 1000-grain weights in maize grown in monoculture, with an average of 287.9 g. The authors suggested that maize in monoculture accumulated more starch due to reduced competition for resources, leading to increased grain weights.

Notably, the yield from the MP100 strategy was 180.22% higher than that of the MN100 strategy, despite both treatments receiving the full nitrogen dose, with the difference attributed to the maize being in monoculture in the MN100 strategy.

Intercropping with peanut under nitrogen fertilization resulted in higher maize yield. These results may be attributed to improved soil physical conditions that promote better root development and more efficient nitrogen use (Zheng et al., 2022). Consistent with this study, Paz et al. (2017) found that maize productivity was higher in the maize + crotalaria treatment compared to monocropping.

Different results were reported by Raza et al. (2021) and Sapucay et al. (2020), where monoculture maize crop presented higher grain productivity. The average productivity over the years was 10,472.4 kg ha^{-1} in the first study and 8,243 kg ha^{-1} in the second.

4.3. Agronomic efficiency in nitrogen use and partial land equivalent ratio

The ability of crops to absorb nitrogen depends on several interrelated variables, such as soil fertility, genetic material, soil moisture, temperature, season, nitrogen uptake patterns, pest and disease incidence, and others. In turn, the mechanisms of intercropping that affect this include root growth, architecture and nitrogen absorption patterns, leaf duration and growth, and nitrogen remobilization within the plant (Lammerts Van Bueren and Struik, 2017; Valenzuela, 2024). Furthermore, one of the main reasons for increased nitrogen efficiency in maize + peanut intercropping is due to biological fixation of atmospheric nitrogen (Feng et al., 2021).

Previous studies have reported similar results to this study, indicating higher nitrogen efficiency in intercropping systems such as maize + peanut (Feng et al., 2021), maize

+ Brachiaria brizantha (Jakelaitis et al., 2005), and cotton + peanut (Qiu et al., 2023) compared to monoculture.

The maize/peanut intercropping system generally achieves a higher advantage in land use efficiency and presents a relative yield superior to maize and peanut monocultures (Feng et al., 2021). According to (Valenzuela, 2024), nitrogen fertilization can significantly contribute to maximizing land use efficiency up to a certain level due to the synergistic increase in nitrogen fertilization, justifying the higher values (1.73).

Similarly, some analyses show good land use efficiency in intercropping, with values around 1.22 (Yu et al., 2015), 1.30 (Martin-Guay et al., 2018), and 1.29 in intercropping maize and 1.16 in intercropping systems without maize (Li et al., 2020).

5. Conclusions

Our results demonstrate that maize/peanut intercropping improves nitrogen fertilizer use efficiency and land use efficiency, while also increasing biomass production. The strategy of applying the full nitrogen dose in combination with peanuts led to higher levels of nitrogen and calcium in maize leaf tissues, as well as enhancements in production components and grain yield. However, complete substitution of nitrogen fertilization in the maize/peanut intercropping system is not recommended and a small amount of N is needed, mainly in the initial stages of plant development. Finally, the intercropping system benefits maize productivity, and the contribution of peanuts to land and nutrient use efficiency supports the continued use of nitrogen fertilization to optimize yields for both crops.

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