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Agronomic efficiency of fertilizers with aggregate technology in the Brazilian Eastern Amazon

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ABSTRACT: The present study aimed to assess the efficiency of monoammonium phosphate (MAP), with controlled-release technology, on cowpea, soybean, and corn in the Brazilian Eastern Amazon edaphoclimatic conditions. It were evaluated MAP conventional, FH Humics MAP that incorporates humic acid, and Potenza MAP that incorporates polymer, and two soils with different clay contents (23.1 and 37.6%), on the growth of cowpea, soybean, and corn, in a greenhouse. Simultaneously, it were evaluated four levels of P (0, 40, 80, and 120 kg ha^{-1} of P_2O_5), for the mentioned formulations on cowpea grain yield, in cerrado, and upland forest environments. Fertilization with MAP Humics and MAP Potenza promotes similar soybean, cowpea, and corn growth, and cowpea grain yield compared to conventional MAP, under greenhouse and field conditions, respectively. MAP formulations promote greater soybean, cowpea, and corn growth, and cowpea grain yield in the sandy loam and cerrado than in sandy clay soil and upland forest environment, respectively. Increasing levels of MAP formulations have no effect on cowpea grain yield in the cerrado but promote linear cowpea grain yield increase in the upland forest environment.

Key words: fertilizer delivery systems; nitrogen leaching; phosphorus use efficiency; *Vigna unguiculata*

Eficiência agronômica de fertilizantes com tecnologia agregada na Amazônia Oriental Brasileira

RESUMO: O presente estudo teve como objetivo avaliar a eficiência do fosfato monoamônico (MAP), com tecnologia de liberação controlada, em feijão-caupi, soja e milho nas condições edafoclimáticas da Amazônia Oriental Brasileira. Foram avaliados MAP convencional, FH Humics MAP que incorpora ácido húmico e Potenza MAP que incorpora polímero, em dois solos com diferentes teores de argila (23,1 e 37,6%), sobre o crescimento de feijão-caupi, soja e milho, em casa de vegetação. Simultaneamente, foram avaliados quatro níveis de P (0, 40, 80 e 120 kg ha^{-1} de P_2O_5) das referidas formulações sobre a produtividade de grãos do feijão-caupi, em ambientes de cerrado e floresta de terra firme. A adubação com FH Humics MAP e Potenza MAP promove crescimento similar de soja, feijão-caupi e milho, e produtividade de grãos do feijão-caupi em relação ao MAP convencional, em condições de casa de vegetação e campo, respectivamente. As formulações MAP promovem maior crescimento da soja, feijão-caupi e do milho, e produtividade de grãos do feijão-caupi em solo franco-argiloarenoso e cerrado do que em solo argiloarenoso e ambiente de floresta de terra firme, respectivamente. O incremento dos níveis das formulações MAP não tem efeito no ambiente do cerrado, mas promove aumento linear da produtividade de grãos do feijão-caupi, em ambiente de floresta de terra firme.

Palavras-chave: sistemas de liberação de fertilizantes; lixiviação de nitrogênio; eficiência do uso do fósforo; *Vigna unguiculata*

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Introduction

The planted area with temporary, permanent, and forestry crops reached 77.9, 5.4, and 9.62 million ha in Brazil in 2020, respectively (IBGE, 2020a; 2020b). Soybean (37.2 million ha), coffee (1.91 million ha), and eucalyptus (7.43 million ha) (IBGE, 2020b) are the most representative in each group. The expansion in the planted area and high productivities achieved in Brazil are associated with the adoption of improved cultivars (Moreira et al., 2017), modern crop practices (Moreira et al., 2020) and plant disease management, as well as the use of fertilizers (Antonangelo et al., 2019) to correct the low natural fertility of heavily weathered Latossolo (Oxisol) and Argissolo (Argisol), the most representatives soil types in Brazil.

Around 42% (2,144,693) of Brazilian agricultural establishments use fertilizers (chemical and/or organic) (IBGE, 2017), and the expansion of the use of fertilizers in Brazil has occurred through the increase of imports, which reached 38.34 million tons in 2021 (Conab, 2021). However, Mani & Mondal (2016) in an extensive review highlighted that around 40-70% of nitrogen, 50-90% of potassium, and 80-90% of phosphorus applied fertilizers, are not used by plants due to the low use efficiency of traditional fertilizers. In the Brazilian tropical climate conditions and weathered soils, the low use efficiency of fertilizer is due to phosphorus loss by adsorption, potassium loss by leaching, and nitrogen loss by leaching and volatilization, reducing its availability to the plants, affecting plant growth and productivity (Moreira et al., 2017; 2020). Borges et al. (2023) observed that fertilization with NPK formulations made with the calcined bone meal promoted greater soybean, cowpea, and corn shoot dry mass in the sandy loam (clay = 231 g kg^{-1}) compared to sandy clay soil (clay = 376 g kg^{-1}) in a three-crop greenhouse experiment, corroborating the assertion that phosphorus adsorption is improved in clayey soils. Therefore, it is reasonable to say that increase in both average productivity and production of Brazilian agriculture can be achieved by increasing both the adoption and the use efficiency of fertilizer.

Practices such as splitting of the fertilizer application (Aquino et al., 2021), intercropping (Tang et al., 2021), crop-forest integration, crop rotation (Moreira et al., 2020), no-till (Antonangelo et al., 2019; Moreira et al., 2020), and different crop successions (Moreira et al., 2020) have been adopted to improve soil volume exploitation by the roots, increase soil organic matter, increase the nutrient content in soil organic matter, at the same time, increase the residual effect of fertilizers in successive crops, reducing losses associated with adsorption and leaching. The selection of highly productive cultivars with high nutrient use efficiency (Moreira et al., 2017), use of the alternative raw material to produce fertilizer, and fertilizer delivery systems to improve fertilizer use efficiency and reduce environmental impacts are promising alternatives (Mani & Mondal, 2016; Antonangelo et al., 2019).

New organomineral fertilizers produced from agro-industrial residues as poultry litter, bone meal, and meat and bone meal (Sá et al., 2017; Nogalska & Załuszniewska, 2021), and fertilizers containing biochar (Borges et al., 2020; Carneiro et al., 2021), polymer (Chagas et al., 2015; Nunes et al., 2022), humic acids (Khan et al., 2019; Gil-Ortiz et al., 2020), Al and Fe activity inhibitors (Chagas et al., 2015), zeolite (Werneck et al., 2012), urease inhibitors (Frazão et al., 2014), chitosan (Adlim et al., 2019), as technologies to control the release and losses of nutrients have been developed and evaluated in different crops. Based on these observations, the present study aimed to assess the efficiency of monoammonium phosphate formulations (MAP) with aggregate technology for controlled release, on soybean, corn, and cowpea in the Brazilian Eastern Amazon edaphoclimatic conditions.

Materials and Methods

Greenhouse experiment

A three-crop greenhouse experiment was carried out in 2018, in the Fazendinha experimental area (0°01’01.51”S, 51°06’35.18”W) at Embrapa Amapá, in Macapá municipality, state of Amapá, Brazil. The experiment had a 3 × 2 factorial design in randomized blocks with four replications. The experimental plots consisted of pots with 5 dm^3 of soil. The treatments consisted of three monoammonium phosphate formulations (MAP), and two soils with different clay contents. It was evaluated the conventional MAP 11-52-00, FH Humics MAP 08-42-00 (Heringer), and Potenza MAP 10-49-00 (FortGreen). FH Humics is a MAP developed by Fertilizantes Heringer that incorporates humic acid, and Potenza is a MAP developed by FortGreen that incorporates polymer. Soils used were collected in Cerrado (cerrado environment) and Mazagão (upland forest environment) experimental areas, located in the Macapá and Mazagão municipalities, respectively. Both experimental areas are owned by Embrapa Amapá and the soils in the experimental areas are Latossolo Amarelo, according to the Brazilian soil classification system (Santos et al., 2018), i.e., an Oxisol. The areas had previously been farmed with cowpea in the Mazagão, and soybean, corn, cowpea, among other crops in the Cerrado. The soils used had the following characteristics at 0-20 cm depth: Cerrado pH 5.5, O.M. 14.3 g kg^{-1}, P 7 mg dm^{-3}, K^+ 0.12 $cmol_c$ dm^{-3}, Ca^{+2} + Mg^{+2} 1.7 $cmol_c$ dm^{-3}, Al^{+3} 0 $cmol_c$ dm^{-3}, H^+ + Al^{+3} 2 $cmol_c$ dm^{-3}, V 47%, CEC 3.8 $cmol_c$ dm^{-3}, texture sandy loam, sand 66.5%, silt 10.4%, and clay 23.1%, and Mazagão pH 4.4, O.M. 23.8 g kg^{-1}, P 7 mg dm^{-3}, K^+ 0.14 $cmol_c$ dm^{-3}, Ca^{+2} + Mg^{+2} 0.7 $cmol_c$ dm^{-3}, Al^{+3} 1.3 $cmol_c$ dm^{-3}, H^+ + Al^{+3} 6.3 $cmol_c$ dm^{-3}, V 11%, CEC 7.1 $cmol_c$ dm^{-3}, texture sandy clay, sand 48.5%, silt 13.9%, and clay 37.6%.

It were evaluated in sequence, using the same pots, the corn (*Zea mays*) cultivar BRS 206, soybean (*Glycine max*) cultivar BRS Tracajá, and cowpea (*Vigna unguiculata*) cultivar BRS Tumucumaque. Five seeds per pot were sown, and seven days after sowing (DAS), thinning was performed keeping two plants per pot. All pots received in each sowing the equivalent of 80 kg ha^{-1} of P_2O_5 as MAP, FH Humics MAP or Potenza MAP, 35 kg ha^{-1} of K_2O as potassium chloride (KCl, 60% of K_2O). Cowpea and soybean received N only as MAP, and corn received 50 kg ha^{-1} of N, part as MAP and supplemented with urea (44% N). Cowpea plants were harvested at 43 DAS and soybean, and corn at 55 DAS, at flowering. Shoots were oven-dried at 65 °C and weighed. The shoots were ground from which the P, K^+, Ca^{2+}, and Mg^{2+} contents were determined. In the end, soil samples were collected for analysis of the remaining P and K^+.

Field experiments

Two further field experiments were carried out in 2018, one in a cerrado environment (00°23'44" N and 51°03'31 W, Macapá, AP, Brazil), and the other in an upland forest environment (0°07'19.2" S and 51°17'57.4" W, Mazagão, AP, Brazil), to evaluate cowpea response to the MAP levels. In the cerrado environment according to the Köppen-Geiger classification, the climate is of the Ami type, with an average annual temperature of 26.3 °C and an average annual rainfall of 2,475 mm. In the upland forest environment, the climate is of the Am type, with an average annual temperature of 27.3 °C and an average annual rainfall of 2,410 mm. Two well-defined climatic seasons are observed in both areas, the first, between December and July, is characterized as rainy (winter), where 90% of annual precipitation occurs and the second, between August and November, is characterized as drought (summer), where 10% of annual precipitation occurs, associated with high temperature and low relative humidity (Tavares, 2014). The sowing was carried out in the periods indicated as low climate risk, corresponding to the 15th and 16th tenths of each year.

The soils and the cowpea cultivar used were the same as used in the greenhouse experiment. A randomized block design with four replications was adopted. It was used plot with 2 × 3 m contained four 3 m lines, spaced at a distance of 0.5 m, with seven cowpea seeds per meter. The treatments consisted of conventional MAP 11-52-00, FH Humics MAP 08-42-00 (Heringer), and Potenza MAP 10-49-00 (FortGreen), and four levels, equivalent of 0, 40, 80, and 120 kg ha^{-1} of P_2O_5. All plots received at sowing the equivalent of 35 kg ha^{-1} of K_2O as KCl. At maturity, 60 DAS cowpea grains were weighed to determine grain yield from the 2 m^2 central of each plot.

Statistical analysis

Analysis of variance (ANOVA) was used, and when confirming a statistically significant value in the F test ($p \leq 0.05$) Tukey tests at the 5% probability level were used to compare differences among formulations and soils on shoot dry mass (SDM), P, Ca^{+2}, Mg^{+2}, and K^+ shoot accumulation, and P and K^+ soil contents. Regression analysis was used to evaluate the effect of applied formulations levels on cowpea grain yield. All statistical analyses were conducted using the software Sisvar (Ferreira, 2019). It was used the agronomic efficiency index (AEI) to evaluate the agronomic efficiency of the MAP with aggregate technology at the applied phosphorus levels, according to Grohskopf et al. (2019). AEI compares the crop grain yields obtained with the phosphate fertilizer with aggregate technology and with the mineral fertilizer (conventional MAP) at the same phosphorus level. The AEI was calculated using the equation: AEI (%) = [(phosphate fertilizer with aggregate technology test level - level 0) / (Mineral fertilizer test level - level 0)] × 100.

Results and Discussion

The use of the MAP formulations containing humic acid or polymer, to control the release of nutrients, promoted the growth of the soybean, corn, and cowpea equivalent to that promoted by the conventional MAP, thus not imposing any restriction on the accumulation of shoot and nutrients, under the conditions evaluated in this study (Tables 1 and 2).

MAP coated with polymers promoted fresh and dry matter, the efficiency of phosphate fertilization, and the use of residual phosphorus in two short 45 days lettuce crops (Chagas et al., 2015). Corn dry matter and grain yield were increased with the use of MAP coated with polymers, especially at base saturation levels of 40% and 50% (Figueiredo et al., 2012). MAP fertilizers coated with organic acid, synthetic organic acid, or humic acid extracted from peat modified the pattern of P release, the movement from the fertilizer granule to the soil, and P availability to corn plants over time, and corn plants accumulated slightly less shoot dry matter than those fertilized with conventional MAP, but they required lower P doses to do so (Teixeira et al., 2016). According to Volf & Rosolem (2020), the potential of phosphates with polymer or humic acid as tools to increase P use efficiency is low since the effects of the base fertilizer and soil characteristics are pre-dominant. The availability of P

Table 1. Summary of the analysis of variance for shoot accumulation (mg per pot) of corn (*Zea mays*), soybean (*Glycine max*), and cowpea (*Vigna unguiculata*) grown in a greenhouse, as a function of the MAP formulation (conventional MAP 11-52-00, FH Humics MAP 08-42-00, and Potenza MAP 10-49-00), and soil type (sandy loam, 23.1% of clay, and sandy clay, 37.6% of clay).

Source of variation	F_c	Pr > Fc	F_c	Pr > Fc	F_c	Pr > Fc
	Corn		Soybean		Cowpea	
MAP formulations	0.868	0.4400^{ns}	0.648	0.5369^{ns}	0.500	0.6162^{ns}
Soils	16.910	0.0009*	122.992	0.0000*	38.275	0.0000*
Interaction MAP formulations × Soils	2.485	0.1169^{ns}	0.004	0.9960^{ns}	0.965	0.4036^{ns}
CV (%)	15.91		21.34		21.25	

Table 2. Shoot dry mass (SDM - g per pot), and P, K^+, Ca^{2+}, and Mg^2 shoot accumulation (mg per pot) of corn (*Zea mays*), soybean (*Glycine max*), and cowpea (*Vigna unguiculata*) grown in a greenhouse, as a function of the MAP formulation (conventional MAP 11-52-00, FH Humics MAP 08-42-00, and Potenza MAP 10-49-00), and soil type (sandy loam, 23.1% of clay, and sandy clay, 37.6% of clay)

MAP formulation	SDM (g per pot)		P (mg per pot)		K^+ (mg per pot)		Ca^{2+} (mg per pot)		Mg^{2+} (mg per pot)	
	Sandy loam	Sandy clay	Sandy loam	Sandy clay	Sandy loam	Sandy clay	Sandy loam	Sandy clay	Sandy loam	Sandy clay
Corn										
Conventional MAP	14.48	9.35	20.38	9.11	299.95	176.40	321.01	158.38	45.85	16.92
FH Humics MAP	12.23	9.53	22.74	10.91	247.39	215.22	270.58	171.52	44.28	9.22
Potenza MAP	11.50	10.33	22.41	9.27	229.43	186.58	268.86	178.05	39.25	10.75
Mean	12.73 a	9.73 b	21.84 a	9.76 b	258.92 a	192.73 b	287.15 a	169.32 b	43.13 a	12.30 b
CV (%)	15.91		18.78		18.75		15.57		53.54	
Soybean										
Conventional MAP	6.43	2.08	14.72	3.89	125.81	35.46	170.03	38.52	41.92	18.10
FH Humics MAP	6.98	2.63	18.09	4.96	162.15	40.39	194.83	52.40	55.24	17.43
Potenza MAP	6.75	2.33	16.53	4.95	151.81	42.59	158.695	52.74	48.95	20.21
Mean	6.72 a	2.34 b	16.45 a	4.60 b	146.59 a	39.48 b	174.52 a	47.82 b	48.71 a	18.53 b
CV (%)	21.34		19.59		25.60		35.68		62.36	
Cowpea										
Conventional MAP	8.73	5.88	27.86	14.07	134.05	125.68	286.82	160.91	102.20	38.86
FH Humics MAP	9.50	5.23	27.28	12.37	150.97	122.61	449.91	147.01	53.22	32.50
Potenza MAP	10.55	5.50	30.97	11.83	172.05	108.50	392.10	135.77	61.10	34.01
Mean	9.59 a	5.53 b	28.70 a	12.76 b	152.36 a	118.93 b	376.30 a	147.90 b	72.18 a	35.12 a
CV (%)	21.25		22.82		23.59		28.62		83.72	

Means followed by the same letter within a row did not differ significantly by Tukey test at the 5% level.

in the soil depends primarily on the soil adsorption capacity, which can be altered by the management of phosphorus fertilization (Volf & Rosolem, 2020) and base saturation (Figueiredo et al., 2012).

Regarding the evaluated soils, it was possible to observe higher shoot dry mass and shoot nutrient accumulation in the three species, when cultivated in sandy loam compared to sandy clay soil. In this case, the difference was significant among the soils, except for Mg^{2+} accumulation in cowpea. In a greenhouse experiment with four successive corn crops, Sá et al. (2017) observed no significant difference in the first, second, and fourth cultivations, but a significantly increased dry matter production in the sandy loam (100 g kg^{-1} clay) compared to clay loam soil (380 g kg^{-1} clay) in the third cultivation. It has been widely reported that weathered clayey soils adsorb most of the P applied as fertilizer, reducing its availability to plants and consequently affecting growth and yield (Silva et al., 2010; Sá et al., 2017; Volf & Rosolem, 2020).

There was no significant difference among the MAP formulations and soils evaluated for the remaining soil content of P and K^+, except among the soil's K^+ content (Table 3). When averaged across the different soils the remaining P content was 21.1, 26.0, and 28.8 mg dm^{-3} when conventional MAP, FH Humics MAP, and Potenza MAP were applied, respectively. Additionally, the remaining P contents difference, between soil with higher and lower clay content, was 8.25, 9.5, and 0.5 mg dm^{-3} for conventional MAP, FH Humics MAP, and Potenza MAP sources, respectively. This result may be associated with the ability of the polymer to change the maximum soil P adsorption capacity, as proposed by Volf & Rosolem (2020), after sequential use.

Table 3. P (mg dm^{-3}) and K^+ ($cmol_c$ dm^{-3}) in the soil after harvested corn (*Zea mays*), soybean (*Glycine max*), and cowpea (*Vigna unguiculata*) grown in a greenhouse, as a function of the MAP formulation (conventional MAP 11-52-00, FH Humics MAP 08-42-00, and Potenza MPA 10-49-00), and soil type (sandy loam, 23.1% of clay, and sandy clay, 37.6% of clay).

MAP formulation	P (mg dm^{-3})		K^+ ($cmol_c$ dm^{-3})	
	Sandy loam	Sandy clay	Sandy loam	Sandy clay
Conventional MAP	25.25	17.00	0.035	0.055
FH Humics MAP	30.75	21.25	0.035	0.052
Potenza MAP	29.00	28.50	0.040	0.047
Mean	28.33	22.25	0.036 b	0.051 a
CV (%)	27.99		22.64	

Means followed by the same letter within a row did not differ significantly by Tukey test at the 5% level.

There was no significant difference between conventional MAP, FH Humics MAP, and Potenza MAP formulations. Cowpea grain yield varied between 418 and 1,183 kg ha^{-1}, and 972 and 1,488 kg ha^{-1} as a function of phosphorus sources and levels (Table 4), in upland forest and cerrado environments, respectively. The results showed that the MAP formulations with the incorporation of humic acids or polymer promoted cowpea grain yield equivalent to that provided by the conventional MAP, not imposing any restriction, as observed for shoot dry mass and nutrient accumulation, under greenhouse conditions. Cowpea grain yield in the forest environment, in

Table 4. Grain yield (kg ha^{-1}) and agronomic efficiency for cowpea (*Vigna unguiculata*) BRS Tumucumaque cultivar as a function of the MAP formulation (conventional MAP 11-52-00, FH Humics MAP 08-42-00, and Potenza MAP 10-49-00) increasing levels, cultivated in cerrado and upland forest environments, respectively in Macapá and Mazagão municipalities, state of Amapá, Brazil.

MAP Levels (P_2O_5 - kg ha^{-1})	Grain yield (kg ha^{-1})			Agronomic efficiency (%)	
	Conventional MAP	FH Humics MAP	Potenza MAP	FH Humics MAP	Potenza MAP
Macapá – cerrado environment (sandy loam soil)					
0	972	1298	1281		
40	1316	1205	1237	-27	-13
80	1488	1143	1474	-30	37
120	1242	1376	1350	29	26
Equation	n.s.*	n.s.	n.s.		
Means	1255 a	1256 a	1335 a		
Mazagão - upland forest environment (sandy clay soil)					
0	418	580	463		
40	667	550	658	-12	78
80	1114	750	1183	24	103
120	932	752	887	33	82
Equation	$y = 484 + 4.97x$	$y = 550 + 1.80x$	$y = 528 + 4.49x$		
R^2	71.00	73.18	56.10		
Means	783 a	658 a	798 a		

n.s.: no significant effect, in terms of P levels as determined by the F test at the 5% level. Coefficient of variation 35.39% and 16.92% to the upland forest and cerrado environments, respectively.

soil with higher clay content, corresponding to 62, 52 and 60% of the grain yield observed in the cerrado environment, in soil with lower clay content, for the sources conventional MAP, FH Humics MAP, and Potenza MAP, respectively. The results achieved for cowpea grain yield observed here in the upland forest environment corroborate the results previously reported by Borges et al. (2021), that observed in a three-year field experiment cowpea grain yield varying from 373 to 984 kg ha^{-1}, when it was used increasing levels of P_2O_5 as triple superphosphate, in an Oxisol with 241 g kg^{-1} of clay, and it was possible to adjust linear equation as a function of the increasing P_2O_5 levels. On the other hand, there was no statistical effect of levels, regardless of source, in the cerrado environment. In cerrado Oxisol, with 179 g kg^{-1} of clay in the State of Roraima, cowpea grain yield increased in response to the applied phosphorus rate until 90 kg ha^{-1} P_2O_5 (Silva et al., 2010). The lack of response to P rates in the cerrado environment may be related to the history of use of the area, given that it has been used for successive experiments that affect the fixation capacity and the availability of P in the soil.

Overall, the agronomic efficiency of conventional MAP was higher than FH Humics MAP and Potenza MAP (Table 4). The agronomic efficiency of FH Humics MAP and Potenza MAP concerning conventional MAP was higher in the upland forest than in the cerrado environment. The agronomic efficiency of FH Humics increased with increasing P levels, in both environments. The Potenza MAP proved to be more efficient for cowpea than the FH Humics MAP, in both environments. The results found in the present study contribute to our understanding of the behavior of fertilizers with controlled nutrient release in the Brazilian Amazon edaphoclimatic conditions. Long-term studies including long-cycle crops should be conducted to better understand the residual effects of these fertilizers, and to increase the efficiency of P use in different agricultural systems.

Conclusions

This study improves our understanding of the relationship between phosphorus supply with fertilizers with aggregate technology, soil clay content, and environmental conditions on cowpea, corn, and soybean plants. We have demonstrated that: (i) fertilization with MAP Humics and MAP Potenza promotes similar soybean, cowpea, and corn shoot dry mass and shoot nutrient accumulation compared to conventional MAP, under greenhouse conditions., (ii) fertilization with MAP formulations promotes greater soybean, corn, and cowpea shoot dry mass and shoot nutrient accumulation in the sandy loam compared to the sandy clay soil, except for cowpea Mg^{2+} shoot accumulation, under greenhouse conditions; (iii) fertilization with MAP Humics and MAP Potenza promotes similar cowpea BRS Tumucumaque cultivar grain yield compared to MAP conventional, in both cerrado and upland forest environments, and (iv) fertilization with increasing levels of MAP formulations promotes linear cowpea BRS Tumucumaque cultivar grain yield increase, in the upland forest, but has no effect in the cerrado environment.

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Compliance with Ethical Standards

Authors contributions: Conceptualization: WLB, AOJ, PCT, JCP; Formal analysis: WLB, JPG; Funding acquisition: WLB, AOJ, PCT, JCP; Investigation: WLB, JPG, AOJ, PCT, JCP;

Methodology: WLB, AOJ, PCT, JCP; Project administration: WLB, AOJ, PCT, JCP; Supervision: WLB, Visualization: WLB, Writing - original draft: WLB, Writing - review & editing: WLB, JPG, AOJ, PCT, JCP.

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Literature Cited

Adlim, M.; Zarlaida, F.; Rahmayani, R. F. I.; Wardani, R. Nutrient release properties of a urea-magnesium-natural rubber composite coated with chitosan. Environmental Technology & Innovation, v.16, e100442, 2019. https://doi.org/10.1016/j.eti.2019.100442.

Antonangelo, J. A.; Firmano, R. F.; Alleoni, L. R. F.; Oliveira Jr., A. Zhang, H. Soybean Production under Continuous Potassium Fertilization in a Long-Term No-Till Oxisol. Agronomy Journal, v. 111, n. 5, p.2462-2471, 2019. https://doi.org/10.2134/agronj2019.02.0084.

Aquino, R. F. B. A.; Cavalcante, A. G.; Clemente, J. M.; Macedo, W. R.; Novais, R. F.; Aquino, L. A. Split fertilization of phosphate in onion as strategy to improve the phopsphorus use efficiency. Scientia Horticulturae, v. 290, e110494, 2021. https://doi.org/10.1016/j.scienta.2021.110494.

Borges, B. M. M. N.; Strauss, M.; Camelo, P. A.; Sohi, S. P.; Franco, H. C. J. Re-use of sugarcane residue as a novel biochar fertiliser - Increased phosphorus use efficiency and plant yield. Journal of Cleaner Production, v.262, e121406, 2020. https://doi.org/10.1016/j.jclepro.2020.121406.

Borges, W, L.; Ferreira, N. S.; Rios, R. M.; Rumjanek, N. G. Liming, fertilization, and rhizobia inoculation on cowpea yield in a Brazilian Amazon upland forest environment. Pesquisa Agropecuária Brasileira, v.56, e02191, 2021. https://doi.org/10.1590/S1678-3921.pab2021.v56.02191.

Borges, W. L.; Garcia, J. P.; Teixeira, P. C.; Polidoro, J. Cowpea, corn, and soybean yield using fertilizer based on the bone meal in the Eastern Amazon. Revista Brasileira de Ciências Agrárias, v.18, n.1, e2577, 2023. https://doi.org/10.5039/agraria.v18i1a2577.

Carneiro, J. S. S.; Ribeiro, I. C. A.; Nardis, B. O.; Barbosa, C. F.; Lustosa Filho, J. F.; Melo, L. C.A. Long-term effect of biochar-based fertilizers application in tropical soil: Agronomic efficiency and phosphorus availability. Science of the Total Environment, v. 760, e143955, 2021. https://doi.org/10.1016/j.scitotenv.2020.143955.

Chagas, W. F. T.; Emrich, E. B.; Guelfi, D. R.; Caputo, A. L. C. Faquin, V. Productive characteristics, nutrition and agronomic efficiency of polymer-coated MAP in lettuce crops. Revista Ciência Agronômica, v. 46, n. 2, p. 266-276, 2015. https://doi.org/10.5935/1806-6690.20150006.

Companhia Nacional de Abastecimento - Conab. Boletim logístico. Ano V. Brasília: Conab, 2021. 21p. https://www.conab.gov.br/info-agro/analises-do-mercado-agropecuario-e-extrativista/boletim-logistico/item/17307-boletim-logistico-dezembro-2021. 10 Jan. 2022.

Ferreira, D. F. SISVAR: A computer analysis system to fixed effects split plot type designs. Revista Brasileira de Biometria, v. 37, n. 4, p. 529-535, 2019. https://doi.org/10.28951/rbb.v37i4.450.

Figueiredo, C. C.; Barbosa, D. V.; Oliveira, S. A.; Fagioli, M.; Sato, J. H. Polymer-coated phosphate fertilizer and liming on the production and morphological parameters of corn. Revista Ciência Agronômica, v. 43, n. 3, p. 446-452, 2012. https://doi.org/10.1590/S1806-66902012000300005.

Frazão, J. J.; Silva, Á. R.; Silva, V. L.; Oliveira, V. A.; Corrêa, R. S. Fertilizantes nitrogenados de eficiência aumentada e ureia na cultura do milho. Revista Brasileira de Engenharia Agrícola e Ambiental, v.18, n.12, p.1262-1267, 2014. https://doi.org/10.1590/1807-1929/agriambi.v18n12p1262-1267.

Gil-Ortiz, R.; Naranjo, M. A.; Ruiz-Navarro, A.; Caballero-Molada, M.; Atares, S.; García, C.; Vicente, O. New eco-friendly polymeric-coated urea fertilizers enhanced crop yield in wheat. Agronomy, v.10, p. 438, 2020. https://doi.org/10.3390/agronomy10030438.

Grohskopf, M. A.; Corrêa, J. C.; Fernandes, D. M.; Benites, V. De M.; Teixeira, P. C.; Cruz, C.V. Phosphate fertilization with organomineral fertilizer on corn crops on a Rhodic Khandiudox with a high phosphorus content. Pesquisa Agropecuária Brasileira, v.54, e00434, 2019. https://doi.org/10.1590/S1678-3921.pab2019.v54.00434.

Instituto Brasileiro de Geografia e Estatística - IBGE. Produção Agrícola Municipal. Principais resultados - 2020a. https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/9117-producao-agricola-municipal-culturas-temporarias-e-permanentes.html?edicao=34923&t=destaques. 07 Jan. 07 2022.

Instituto Brasileiro de Geografia e Estatística - IBGE. Produção da Extração Vegetal e da Silvicultura. Principais resultados - 2020b. https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/9105-producao-da-extracao-vegetal-e-da-silvicultura.html?edicao=31773&t=destaques. 07 Jan. 2022.

Instituto Brasileiro de Geografia e Estatística - IBGE. Censo Agropecuário. 2017. https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/21814-2017-censo-agropecuario.html. 07 Jan. 2022.

Khan, M. Z.; Ahmed, H.; Ahmed, S.; Khan, A.; Khan, R. U.; Hussain, F.; Hayat, A.; Sarwar, S. Formulation of humic substances coated fertilizer and its use to enhance K fertilizer use efficiency for tomato under greenhouse conditions. Journal of Plant Nutrition, v. 42, n. 6, p. 26 - 633, 2019. https://doi.org/10.1080/01904167.2019.1568462.

Mani, P. K.; Mondal, S. Agri-nanotechniques for plant availability of nutrients. In: Kole, C.; Kumar, D.; Khodakovskaya, M. (Eds.) Plant Nanotechnology. Chandra: Springer, 2016. p.263-303. https://doi.org/10.1007/978-3-319-42154-4_11.

Moreira, A.; Moraes, L. A. C.; Moretti, L. G. Yield, Yield Components, Soil Chemical Properties, Plant Physiology, and Phosphorus Use Efficiency in Soybean Genotypes. Communications in Soil Science and Plant Analysis, v. 48, n. 20, p. 2464 - 2476, 2017. https://doi.org/10.1080/00103624.2017.1416126.

Moreira, A.; Moraes, L. A. C.; Petineli, R. Phosphate Fertilizer in Soybean-Wheat Cropping System Under No-Till Management. Frontiers in Sustainable Food Systems, v. 4, e564586, 2020. https://doi.org/10.3389/fsufs.2020.564586.

Nogalska, A.; Załuszniewska, A. The effect of meat and bone meal (MBM) on crop yields, nitrogen content and uptake, and soil mineral nitrogen balance. Agronomy, v.11, n. 11, e2307, 2021. https://doi.org/10.3390/agronomy11112307.

Nunes, A. P. P.; Santos, C. F.; Guelfi, D. Interfaces between biodegradable organic matrices coating and MAP fertilizer for improve use efficiency. Science of the Total Environment, v.804, e149896, 2022. https://doi.org/10.1016/j.scitotenv.2021.149896.

Sá, J. M.; Jantalia, C. P.; Teixeira, P. C.; Polidoro, J. C.; Benites, V. M.; Araújo, A. P. Agronomic and P recovery efficiency of organomineral phosphate fertilizer from poultry litter in sandy and clayey soils. Pesquisa Agropecuária Brasileira, v.52, n.9, p.786-793, 2017. https://doi.org/10.1590/S0100-204X2017000900011.

Santos, H. G.; Jacomine, P. K. T.; Anjos, L. H. C.; Oliveira, V. Á.; Lumbreras, J. F.; Coelho, M. R.; Almeida, J. A.; Araújo Filho, J. C.; Oliveira, J. B.; Cunha, T. J. F. Sistema brasileiro de classificação de solos. 5. ed. Brasília: Embrapa, 2018. 356p.

Silva, A.J.; Uchôa, S. C. P.; Alves, J. M. A.; Lima, A. C. S.; Santos, C. S. V.; Oliveira, J. M. F.; Melo, V. F. Response of cowpea (*Vigna unguiculata* (L.) Walp.) to phosphorus fertilization levels and application forms in Yellow Latosol of Roraima State/Brazil. Acta Amazônica, v. 40, n. 1, p. 31-36, 2010. https://doi.org/10.1590/s0044-59672010000100004.

Tang, X.; Zhang, C.; Yu, Y.; Shen, J.; van der Werf, W.; Zhang, F. Intercropping legumes and cereals increases phosphorus use efficiency; a meta-analysis. Plant Soil, v. 460, p. 89-104, 2021. https://doi.org/10.1007/s11104-020-04768-x.

Tavares, J. P. N. Características da climatologia de Macapá-AP. Caminhos da Geografia, v. 15, n. 50, p.138-151, 2014. https://doi.org/10.14393/RCG155026031.

Teixeira, R. S.; Silva, I. R.; Sousa, R. N.; Mattiello, E. M.; Soares, E. M. B. Organic acid coated-slow-release phosphorus fertilizers improve P availability and maize growth in a tropical soil. Journal of Soil Science and Plant Nutrition, v. 16, n. 4, p.1097-1112, 2016. https://doi.org/10.4067/S0718-95162016005000081.

Volf, M. R.; Rosolem, C. A. Soil P diffusion and availability modified by controlled-release P fertilizers. Journal of Soil Science and Plant Nutrition, v. 21, p.162-172, 2021. https://doi.org/10.1007/s42729-020-00350-7.

Werneck, C. G.; Breda, F. A.; Zonta, E.; Lima, E.; Polidoro, J. C.; Balieiro, F. C.; Bernardi, A. C. C. Volatilização de amônia proveniente de ureia com zeólita natural. Pesquisa Agropecuária Brasileira, v.47, n.3, p.466-470, 2012. https://doi.org/10.1590/S0100-204X2012000300020.