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Contributions of organic residues to the establishment of *Stylosanthes capitata* in degraded soil

Contribuições de resíduos orgânicos para o estabelecimento de *Stylosanthes capitata* em solo degradado

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Highlights

Sugarcane bagasse ash, sewage sludge and aquatic macrophytes increased Ca^{2+} in the soil.
Sewage sludge (20 t ha^{-1}) boosts shoot fresh biomass, root system volume, and dry mass.
The combined organic residues facilitated the healthy establishment of *S. capitata.*

Abstract

Organic residues can improve the fertility of degraded soils and help restore vegetation. This study was structured to evaluate the contribution of residues in the chemical conditioning of degraded soil and the establishment of *Stylosanthes capitata.* The experiment was conducted under protected cultivation conditions in a completely randomized experimental design, following a 4 x 4 x 2 factorial scheme with three replications per treatment and two plants per replication (pots with 10 kg of soil). Residues, aquatic macrophytes (MAC), and sewage sludge (SLU) were added to the soil at doses of 0, 10, 20, and 30 t ha^{-1}. Sugarcane bagasse ash (ASH) was incorporated into the soil at doses of 0 and 20 t ha^{-1} 10 days before SLU, MAC, and *S. capitata* seeds. The soil was analyzed for fertility and the plants for height, shoot and root fresh and dry mass, and root volume 120 days after sowing. ASH, SLU, and MAC residues increased pH and organic matter, phosphorus, and calcium contents, facilitating plant establishment, standing out the dose of 20 t ha^{-1} for SLU and MAC. Therefore, the use of these residues can be recommended both as chemical soil amendments and facilitators for *S. capitata* establishment.

Key words: Aquatic macrophytes. Sewage sludge. Sugarcane bagasse ash. Soil fertility.

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Resumo

Resíduos orgânicos podem melhorar a fertilidade de solos degradados e auxiliar no restabelecimento da vegetação. Este trabalho foi estruturado para avaliar a contribuição de resíduos no condicionamento químico de um solo degradado e no estabelecimento de *Stylosanthes capitata.* O experimento foi conduzido em condição de cultivo protegido, em delineamento experimental inteiramente casualizado, em esquema fatorial 4 x 4 x 2, com 3 repetições por tratamento e 2 plantas por repetição (vasos com 10 kg de solo). Os resíduos, macrófitas aquáticas (MAC) e lodo de esgoto (LOD) foram adicionados ao solo nas doses 0, 10, 20 e 30 t ha^{-1}. A cinza do bagaço da cana-de-açúcar (CZA) foi incorporada ao solo nas doses 0 e 20 t ha^{-1}, dez dias antes do LOD, da MAC e das sementes de S. capitata. Transcorridos 120 dias da semeadura, o solo foi analisado para fertilidade e as plantas para altura, massa fresca e seca da parte aérea e do sistema radicular e volume de raízes. Os resíduos CZA, LOD e MAC elevaram pH, teores de matéria orgânica, fósforo e cálcio do solo, facilitando o estabelecimento da planta, com destaque para a dose de 20 t ha^{-1} para LOD e MAC. Assim, pode-se recomendar o uso destes resíduos tanto como condicionantes químicos do solo como facilitadores no estabelecimento do *S. capitata.*

Palavras-chave: Macrófitas aquáticas. Lodo de esgoto. Cinza do bagaço da cana-de-açúcar. Fertilidade do solo.

Introduction

The Cerrado is known for its high biodiversity and for having a high concentration of endemic species, but it has experienced an increasing loss of habitats in the last fifty years (Oliveira et al., 2019). Considered the second-largest Brazilian biome, it occupies around 25% of the national territory and boats significant biodiversity, yet it is undervalued in terms of conservation efforts (Rocha et al., 2022), making it vulnerable to habitat destruction and fragmentation. This has led to its classification as one of the most threatened regions on the planet (Hidasi et al., 2019; Macedo et al., 2020).

The 1970s, considered a negative reference in Brazil in terms of environmental degradation, was marked by the disordered use and occupation of land to expand territories and agricultural production (Bittar, 2011). An example is the construction of the Ilha Solteira Hydroelectric Power Plant (HPP), one of the largest hydroelectric projects in Brazil at the time, marked by a comprehensive environmental impact (Martin, 2018). We recognize the significance of the energy generation process, especially generation through the use of water, considered one of the least harmful solutions to the environment. However, dam constructions often lead to severe degradation in large surrounding areas, where vegetation and soil layers are suppressed. This results in the creation of “borrowed areas,” from where land is removed for riprap. Addicionally, the construction process can lead to the emergence of unstable slopes, humid, flooded areas, or extensive flooded areas required for the formation of the reservoir (Alves & Souza, 2008).

According to Rodrigues et al. (2007), the construction process of the Ilha Solteira HPP left a high-density material on the surface, classified as "geological residue in a flat remaining area," which exhibits a reduced infiltration rate and low fertility. These soil conditions, associated with the loss of the seed bank and underground regrowth structures (Pilon et al., 2021), due to area stripping, as well as the removal of fauna, have hindered the reestablishment the vegetation cover, impacting the ecosystem (Espejo et al., 2018). In such cases, with no natural or slow recovery (Durigan et al., 2011), the assistance of well-planned anthropogenic actions is necessary to mitigate the existing degradation process (Guerra et al., 2020; Souza et al., 2020).

The insertion of vegetation in these areas has multiple functions, and the selection of species must be carefully analyzed. Legumes, in particular, present promising qualities, as they contribute to the addition of organic matter (OM), biological nitrogen fixation (BNF), facilitation of microbiological activity, improvement of soil aspects such as fertility and structure, and promotion of the establishment of other plant species (Costa et al., 2014; Freitag et al., 2018).

Pencilflower (*Stylosanthes* sp.), a genus of legumes that includes the species *S. capitata* used in this study, is among the many plant species available in the region. It enriches the soil with nutrients and contributes to increased vegetation cover, thus stimulating the recovery of degraded areas (Ortega et al., 2020). Widely utilized for intercropping and pasture restoration, this species is common in the Cerrado, fix nitrogen biologically and presents tolerance to acidic and low phosphorus (P) soil content (Empresa Brasileira de Pesquisa Agropecuária [EMBRAPA], 2007).

These traits represent good options for the recovery of degraded areas, especially in situations where soil conditions are not favorable to the natural re-establishment of vegetation. However, the soil conditions in areas such as those described above need to be improved for the establishment of vegetation. The incorporation of organic residues may aid in restoring vegetation, enhancing microbiological activity, and resuming environmental dynamics and biogeochemical cycles (Brown et al., 2014), minimizing existing impacts .

The addition of organic residues, such as sewage sludge, aquatic macrophytes, and ash produced in the pyrolysis process, can enhance soil infiltration and permeability, increasing porosity (Al-Kindi & Abed, 2016). Sewage sludge is a residual and semi-solid material, a by-product of domestic and industrial effluent treatment, rich in organic matter (OM) and with potential for fertilization (Carvalho et al., 2020). Its use as an amendment in the subsoil of borrow areas represents a low-cost alternative and also a method of disposing of this sludge. The biomass of aquatic macrophytes added to the soil provides increases in OM, P, exchangeable calcium (Ca^{2+}), and magnesium (Mg^{2+}), and microbial activity (Machado et al., 2014), indicating potential for the recovery of degraded soils. The ash produced from sugarcane bagasse in boilers at sugar and alcohol plants is another residue that has been used in agriculture and for the recovery of degraded soils. Its use provides macro-and micronutrients, increases moisture retention, and partially corrects soil acidity (Boni et al., 2017; Prado et al., 2020).

These residues, each with their own characteristics, have the potencial to improve the conditions of degraded soil, thereby contributing to the reestablishment of vegetation. In this sense, this study aimed to evaluate the contributions of organic residues (ash, sewage sludge, and aquatic macrophytes) to the establishment of *S. capitata* in degraded soil.

Material and Methods

This study was conducted in pots from October 2019 to February 2020 in a protected cultivation system at the experimental area of ETEC – Escola Técnica Estadual Prof. Dr. Antônio Eufrásio de Toledo, in the municipality of Presidente Prudente, São Paulo State, Brazil. The regional climate is classified as tropical (Aw), according to the Köppen (Alvares et al., 2013), characterized by hot conditions (mean maximum temperatures between 27 and 29 °C) and rainy summers/autumns (monthly precipitation ranging from 150 to 200 mm), with mild (mean minimum temperatures between 18 and 22 °C) and dry winter (monthly precipitation of 20 to 50 mm) (Rolim et al., 2007).

The experimental units consisted of 15 L pots filled with 10 kg of soil characterized as exposed subsoil. This soil was collected in a borrow area produced during the construction of the Ilha Solteira HPP in the 1960s. The area is situated within the Teaching, Research, and Extension Farm of the School of Engineering at UNESP, Ilha Solteira Campus, in the municipality of Selvíria, State of Mato Grosso do Sul, Brazil, positioned on the right bank of the Paraná River. The soil of the area was classified by Demattê (1980) and updated according to the Brazilian Soil Classification System (Santos et al., 2018) as an Oxisol (Latossolo Vermelho distrófico) and the original vegetation cover was described as Cerrado. The initial chemical characterization (Table 1), followed the methodology proposed by Raij et al. (2001). The treatments consisted of the incorporation of three organic residues into the subsoil: aquatic macrophytes (MAC), sewage sludge (SLU), and sugarcane bagasse ash (ASH). These treatments were established following a completely randomized experimental design in a 4 x 4 x 2 factorial scheme, with three replications per treatment and two plants per replication. The first and second factors, MAC and SLU, respectively, were incorporated at doses of 0, 10, 20, and 30 t ha^{-1}, while ASH, the third factor, was added to the soil at doses of 0 and 20 t ha^{-1}.

The MAC were collected from the Jupiá HPP reservoir, in Três Lagoas, State of Mato Grosso do Sul, Brazil. They were left to dry and composting for 180 days, deposited on the surface, in a covered place. The SLU, coming from the Presidente Prudente Sewage Treatment Station, where it underwent biological treatment, followed by drying in the shade until it reached 10% moisture content, and finally, it was homogenized. The ASH was donated by the Vale do Paraná S/N, located in Suzanápolis, State of São Paulo, Brazil, resulting from the burning of sugarcane bagasse. The residues were chemically characterized (Tables 1 and 2) by the methodologies of Raij et al. (2001) and Malavolta et al. (1997).

Table 1

Initial chemical characterization of the subsoil and the residues aquatic macrophytes (MAC), sewage sludge (SLU), and sugarcane bagasse ash (ASH), following the methodology by Raij et al. (2001)

Material	P mg kg^{-1}	MO g kg^{-1}	pH $CaCl_2$	K^+	Ca^{2+}	Mg^{2+}	H+Al	Al^{3+}	SB	CEC
				------------------- (mmolc kg^{-1}) ---------------------						
MAC	146.8	146.8	7.1	9.9	1222.0	66.5	9.6	0	1299	1306.0
SLU	108.2	108.2	7.8	6.4	712.6	97.0	6.7	0	816	822.7
ASH	405.4	405.4	8.1	17.9	255.4	43.6	5.4	0	317	322.3

P = phosphorus, OM = organic matter, pH = soil reaction, K^+ = potassium, Ca^{2+} = calcium, Mg^{2+} = magnesium, H+Al = potential acidity, Al^{3+} = aluminium, SB = sum of bases, CEC = cation exchange capacity.

Table 2

Chemical characterization of aquatic macrophytes (MAC), sewage sludge (SLU), and sugarcane bagasse ash (ASH), following the methodology by Malavolta et al. (1997)

Material	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
	---------------------- (g kg^{-1}) ----------------------						--------------- (mg kg^{-1}) ----------------				
MAC	9.8	1.5	2.9	86.4	2.9	6.2	4.2	212.0	7403	732.3	297.0
SLU	20.8	8.2	2.9	158.3	5.3	11.0	6.5	242.2	3636	119.9	199.0
ASH	1.7	8.1	11.4	73.3	12.2	2.8	13.6	212.4	4076	791.1	119.5

N = nitrogen, P = phosphorus, K^+ = potassium, Ca^{2+} = calcium, Mg^{2+} = magnesium, S = sulfur, B = boron, Cu = copper, Fe = iron, Mn = manganese, Zn = zinc.

After 10 days of ASH incorporation into the degraded soil, the remaining residues (MAC and SLU) were incorporated and the soil was homogenized. Subsequently, five seeds were sown per pot. The seeds were obtained commercially, under the identification of "estilosantes Campo Grande", prepared from a mixture of seeds from improved strains of *S. capitata* and *S. macrocephala* (EMBRAPA, 2007). The experiment received two daily waterings (morning and afternoon) using a sprinkler system (3 minutes in duration). Thinning was carried out 45 days after sowing, keeping two seedlings of *S. capitata* per pot, which germinated and established more quickly than *S. macrocephala.*

Initial growth was evaluated at 120 days after sowing for height (HEI – the distance between the apical bud and the collar), shoot fresh mass (SFM) and shoot dry mass (SDM), root fresh mass (RFM) and root dry mass (RDM) (Carneiro, 1995), and root volume (RV) (Zenzen et al., 2007). The soil, separated from the roots, was prepared (air-dried and sifted through a 2 mm mesh) and chemically characterized following the methodology by Raij et al. (2001), and nitrogen (N) was determined by the Kjeldahl method (Malavolta et al., 1997).

The data were tested for the hypothesis of normality using the Shapiro-Wilk test and, once the assumptions were met, analysis of variance was carried out by applying the F-test ($p \leq 0.05$) to detect differences between treatments. Analysis of variance was performed in the regression for significant differences between doses. Statistical analyses were conducted using the SISVAR software (Ferreira, 2019).

Results and Discussion

The evaluated chemical attributes were influenced by ASH at 120 days after sowing. N, OM, Ca^{2+}, and Mg^{2+} contents, as well as soil pH, increased in the presence of 20 t ha^{-1} of ASH, while H+Al, P and K^{+} contents decreased. Addicionally, the sum of bases, CEC, and base saturation also increased as a consequence of the increases in the bases (Ca^{2+} and Mg^{2+}). This trend was consistent with the addition of MAC and SLU since both add Ca^{2+} to the soil (Tables 1, 2, and 3).

Feitosa et al. (2009) also emphasized the nutrient contribution of ASH. The authors pointed out ASH as a source of macro-and micronutrients in the soil, while Ferreira et al. (2012) found that the addition of ASH in acidic soils reduced the toxicity by Al^{3+}. In the present study, the soil pH varied from 6.6 to 7.4 and exchangeable Al^{3+} was no longer available (Table 4). This behavior corroborates with Shetty et al. (2021) findings, as ASH alkalinity (pH 8.1) in acidic soils contributes to an increase in pH. The presence of ASH led to a pH = 7.2, Ca^{2+} = 62.4 mmolc kg^{-1}, and P = 6.7 mg kg^{-1}, while its absence led to a pH = 6.7, Ca^{2+} = 40.6 mmolc kg^{-1}, and P = 18.1 mg kg^{-1}. This suggests the formation of calcium phosphate in the presence of 20 t ha^{-1} of ASH, leading to decreased in labile P content in the soil.

The MAC doses promoted linear increases in the OM and Ca^{2+} contents in the soil (Table 3), with OM increasing by 7% and Ca^{2+} by 59% with the addition of 30 t ha^{-1} of MAC. The significant role of macrophytes relative to Ca^{2+} can be attributed to the presence of calcium in their composition (Table 2). On the other hand, P contents decreased in the presence of MAC ($\hat{y} = 3.78 - 0.09x$) and increased by 123% in the presence of the highest dose (30 t ha^{-1}) of SLU ($\hat{y} = 7.70 + 0.31x$), highlighting SLU as a P source (Table 3). Similar results has been reported in other studies, showing the importance of sludge in increasing P and N contents in the soil (Černe et al., 2019; Alvarenga et al., 2015).

The reduction in P contents with MAC application can be attributed to its low phosphorus mobility in the soil (Tarafdar, 2019), and the possibility of P being adsorbed onto Fe and Al oxides surfaces. However, in the presence of pH > 7.0 and reduced H+Al, P can be immobilized as calcium phosphate (Camargo et al., 2010; Olibone & Rosolem, 2010).

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Table 3

Mean values for nitrogen (N), phosphorus (P), organic matter (OM), soil reaction (pH), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), potential acidity (H+Al), and F values, overall mean, coefficient of variation (CV), regression equations, and coefficient of determination (R^2) for treatments (doses (t ha^{-1}) of sugarcane bagasse ash -ASH, aquatic macrophytes-MAC, and sewage sludge-SLU)

Sources of Variations	N (g kg^{-1})	P (mg kg^{-1})	OM (g kg^{-1})	pH ($CaCl_2$)	K$^+$	Ca^{2+}	Mg^{2+}	H+AL
					--------------- (mmolc kg^{-1}) ---------------			
	F Values							
ASH	5.52 *	252.25**	15.56**	58.70**	75.41**	41.54**	24.20**	6.76 *
MAC	2.58^{ns}	7.87**	5.60**	1.60 ^{ns}	1.05 ^{ns}	10.79**	0.28 ^{ns}	1.15 ^{ns}
SLU	3.74 *	32.07**	2.46 ^{ns}	4.19 *	8.84**	26.92**	0.36 ^{ns}	2.19 ^{ns}
ASH X MAC	0.98 ^{ns}	4.05 ^{ns}	1.52 ^{ns}	2.43 ^{ns}	0.56 ^{ns}	2.99 *	3.18 *	1.41 ^{ns}
ASH X SLU	2.03 ^{ns}	0.86 ^{ns}	2.77 *	2.85 *	1.56 ^{ns}	5.77**	1.15 ^{ns}	1.71 ^{ns}
MAC X SLU	1.88 ^{ns}	5.76**	1.13 ^{ns}	2.96 *	0.83 ^{ns}	0.97 ^{ns}	2.04 *	0.83 ^{ns}
Overall means	0.25	12.4	8.99	6.91	0.89	52	10.36	11.68
CV (%)	27	28	7	5	21	32	24	23
ASH (doses t ha^{-1})	Means							
0	0.24 b	18.1 a	8.8 b	6.7 b	1.1 a	40.6 b	9.1 b	12.4 a
20	0.27 a	6.7 b	9.2 a	7.2 a	0.7 b	62.4 a	11.6 a	11.0 b
MAC (doses t ha^{-1})	Means							
0	0.2	13.3	8.8	6.7	0.9	42.7	10.6	12.4
10	0.3	14.6	8.9	7.0	0.9	47.5	10.5	11.3
20	0.3	10.0	8.9	6.8	0.9	48.0	10.2	11.9
30	0.3	11.7	9.4	7.0	1.0	67.8	10.1	11.1
SLU (doses t ha^{-1})	Means							
0	0.2	7.7	8.8	6.7	1.0	31.1	10.3	12.5
10	0.3	11.0	9.0	7.0	0.9	46.3	10.7	12.2
20	0.3	13.6	9.0	7.0	0.8	55.6	10.5	11.1
30	0.3	17.2	9.2	7.0	0.8	73.0	10.0	10.9

Means followed by the same letter, in the columns do not differ significantly by Tukey test ($p \leq 0.05$). **, * and ^{ns} represent significant values for $p \leq 0.01$, $p \leq 0.05$, and non significant values, respectively. **Significant regression equations for doses of MAC: P** ($\hat{y}$=13.78 – 0.09 x; R^2=0.3740; Pr/F=8.836**). **OM** ($\hat{y}$=8.71 + 0.02 x; R^2=0.7093; Pr/F=11.912**). **Ca^{2+}** ($\hat{y}$=40.17 + 0.76 x; R^2=0.7727; Pr/F=25.014**). **Significant regression equations for doses of SLU: N** ($\hat{y}$=0.22 +0.0020 x; R^2=0.8723; Pr/F=9.772**). **P** ($\hat{y}$=7. 70 + 0.31 x; R^2=0.9964; Pr/F=95.883**). **pH** ($\hat{y}$=6.79 + 0.01 x; R^2=0.6665; Pr/F=8.379**). **K^+** ($\hat{y}$=1.01 – 0.01 x R^2=0.8763; Pr/F=23.229**). **Ca^{2+}** ($\hat{y}$=31.25 + 1.35 x; R^2=0.9884; Pr/F= 878.813**). **H+Al** ($\hat{y}$=12.56 - 0.06 x; R^2=0.9130; Pr/F=5.988**). Pr/F = Probability of F.

Table 4

Mean values for calcium (Ca^{2+}) and magnesium (Mg^{2+}) in the unfolding of the interaction between sugarcane bagasse ash (ASH) x aquatic macrophytes (MAC), and organic matter (OM), soil reaction (pH), and calcium (Ca^{2+}) in the unfolding of the interaction between sugarcane bagasse ash (ASH) x sewage sludge (SLU), F values, regression equations, and coefficient of determination (R^2) for *Stylosanthes capitata*

ASH	0 (t ha^{-1})	10 (t ha^{-1})	20 (t ha^{-1})	30 (t ha^{-1})	F Values
	Doses of MAC (t ha^{-1})				
	-------------------- Ca^{2+} (mmolc kg^{-1}) --------------------				
With	47.0 a	55.2 a	63.1 a	84.3 a	11.204**
Without	38.5 a	39.8 b	33.0 b	51.3 b	0.061 ^{ns}
F Values	1.611 ^{ns}	5.213*	19.776**	23.917**	
	-------------------- Mg^{2+} (mmolc kg^{-1}) --------------------				
With	11.4 a	11.3 a	12.8 a	11.0 a	1.224 ^{ns}
Without	9.9 a	9.8 a	7.5 b	9.2 a	2.239 ^{ns}
F Values	2.275 ^{ns}	1.954 ^{ns}	26.236**	3.275 ^{ns}	
	Doses of SLU (t ha^{-1})				
	----------------------- OM (g kg^{-1}) -----------------------				
With	8.9 a	9.0 a	9.2 a	9.8 a	4.451 *
Without	8.6 a	8.8 a	8.9 a	8.7 b	0.784 ^{ns}
F Values	1.882 ^{ns}	1.059 ^{ns}	1.059 ^{ns}	19.882**	
	----------------------------- pH (CaCl$_2$) ---------------------------				
With	6.9 a	7.2 a	7.2 a	7.4 a	4.638 *
Without	6.6 b	6.7 b	6.9 b	6.6 b	2.399 ^{ns}
F Values	7.695 *	13.195**	6.979 *	39.369**	
	-------------------- Ca^{2+} (mmolc kg^{-1}) --------------------				
With	36.1 a	56.9 a	61.2 a	95. 5 a	26.525**
Without	26.2 a	35.6 b	50.1 b	50.6 b	6.162**
F Values	2.142 ^{ns}	9.914 *	2.672 ^{ns}	44.132**	

Means followed by the same letter, in the columns, do not differ significantly by Tukey test ($p \leq 0.05$). **, * and ^{ns} represent significant values for $p \leq 0.01$, $p \leq 0.05$, and no significant, respectively. **Significant regression equations in the unfolding ASH x MAC: Ca^{2+} with ASH** ($\hat{y}$= 44.45 + 1.20 x; R^2=0.9318; Pr/F=31.319**). **Significant regression equations in the unfolding ASH x SLU: OM with ASH** ($\hat{y}$= 8.84 + 0.03 x; R^2 = 0.8604; Pr/F = 5.897*). **pH with ASH** ($\hat{y}$=6.94 + 0.01 x; R^2=0.9060; Pr/F =12.606**), **pH without ASH** ($\hat{y}$=6.53 + 0.03 x – 0.0011 x^2; R^2=0.8604; Pr/F = 5.897*), **Ca^{2+} with ASH** ($\hat{y}$= 35.03 + 1.82 x; R^2=0.9154; Pr/F = 72.841**), **Ca^{2+} without ASH** ($\hat{y}$=27.47 + 0.88 x; R^2=0.9870; Pr/F = 16.807**).

The addition of SLU, raising pH to 7.0, increased in N and Ca^{2+} contents but decreased K^+ (from 1.0 to 0.8 mmolc dm^{-3}). Part of the K^+ added to the soil through SLU (2.85 g kg^{-1}) was readily available (6.4 mmolc kg^{-1}) and may have been leached throughout the experimental period due to daily irrigation. Paglia et al. (2007) recommended the use of potassium fertilization as a complement to the addition of sewage sludge to the soil due to K^+ leaching.

H+Al decreased by 11.3% with ASH addition, a opposite behavior to that reported by Ebeling et al. (2008), who observed an increase in H+Al and OM. In the present experiment, OM increased and H+Al decreased, though it remained high (Table 3). The sum of bases exhibited a linear increase with the addition of organic residues, reaching 45% with the highest dose of MAC (30 t ha^{-1}) and 98% with the highest dose of SLU (30 t ha^{-1}), consistent with increases in Ca^{2+} and repeating for CEC and bases saturation. Variables dependent on negative charges in the soil can be favored by OM addition and, consequently, SLU + MAC addition (Alvarenga et al., 2015) since both add OM to the soil.

The interaction between SLU x MAC highlights the contribution of MAC to the addition of Ca^{2+} to the soil and the increase in the sum of bases, while the interaction ASH x SLU reveals the contribution of SLU to the addition of Ca^{2+} and the increase in soil pH. Regarding the interaction of ASH with MAC and ASH with SLU (Table 4), the best results for Ca^{2+}, Mg^{2+}, and the sum of bases were verified in the presence of ASH + SLU, while those for OM, pH, and Ca^{2+} were observed in the presence of ASH + MAC. These results demonstrate the combined effects of ASH associated with residues and indicate that the applied residues have the potential to improve soil fertility by increasing base contents, particularly Ca^{2+}.

The interaction between MAC and SLU (Table 5) reveals quadratic behavior for P in the absence and with 30 t ha^{-1} of SLU and indicates that 17.5 t ha^{-1} would be sufficient to obtain the highest P content under the conditions defined in this study. The pH varied depending on MAC and SLU, it increases in the absence or with 10 t ha^{-1} of MAC. It is estimated that 22.8 t ha^{-1} of SLU would be enough to raise the pH to 7.4.

The plant variables HEI, SFM, SDM, RFM, RDM, and RV presented higher values with the addition of 20 t ha^{-1} of ASH (Table 6), while the incorporation of MAC led to linear increases for most plant variables depending on the applied doses, except for RFM and RDM, which displayed a quadratic response with maximum points at 19 and 17.5 t ha^{-1}, respectively. These results indicate that the tested doses were sufficient for *S. capitata* root growth. In a field study by Andrade et al. (2010) plants reached heights between 6 and 9 cm after six months.

These findings indicate that the conditions in the present experiment did not hinder the initial plant growth, withsome treatments showing a height of 4.9 cm after 120 days (Table 6). *S. capitata* exhibited positive and linear increases in HEI, SDM, and RV depending on the applied doses of SLU, indicating that SLU can facilitate the vegetation establishment process in areas with degraded soil conditions.

However, SFM, RFM, and RDM demonstrated quadratic responses to the SLU doses, with maximum points (MP) at

10.7, 13.4, and 13.0 t ha^{-1}, respectively, implying that these doses would be sufficient for biomass production in both the shoot and root system. In situations of low fertility, plants may invest first in the root system to increase the volume of soil explored (Fageria & Moreira, 2011). Mizobata et al. (2017) reported that MAC application contributed to an increase in the root fresh matter of baru, a Cerrado tree legume, by approximately 0.62 g for every 10 t ha^{-1} of MAC, evidencing its importance as a supplier of nutrients and OM essential for plant growth.

Plant growth responded positively to SLU but lower doses may be sufficient (Table 6). However, the adjustment of the aforementioned models, although significant, showed coefficients of determination below 60%, indicating that the quadratic model does not fit very well with the obtained results (Montgomery et al., 2012).

The interaction between ASH x MAC, as well as ASH x SLU for HEI, RFM, and RDM suggests that the tested doses adequately support *S. capitata* root growth, and the highest measurements were achieved with MAC doses between 13 and 23 t ha^{-1} in the absence of ASH, and SLU doses could be even lower for RFM and RDM, that is, between 10 and 16 t ha^{-1} in the presence or absence of ASH (Table 7). The behavior of the other variables in the interaction was linear and not limited to SLU or MAC doses, indicating a quadratic behavior as a reference in choosing the best SLU and MAC doses to be applied.

Importantly, both the ASH + MAC and ASH + SLU combinations favored the growth of the *S. capitata* root system, resulting in higher RV, RFM, and RDM. Additionally, the ASH + MAC association also enhanced growth in HEI (Table 7), probably due increased RV, which may facilitate the nutrients acquisition, thereby contributing to higher growth in HEI.

The MAC x SLU interaction showed that RDM was higher in the presence of 20 t ha^{-1} of MAC and 20 t ha^{-1} of SLU, while 10 t ha^{-1} of SLU and 20 t ha^{-1} of MAC yielded the best results for HEI. In order words, the highest increases occurred under these conditions (Figures 1 and 2). The incorporation of ASH, MAC, and SLU not only conditioned the soil chemically but also contributed to the initial growth of *S. capitata,* highlighting the effectiveness of 20 t ha^{-1} doses for MAC, SLU, and ASH.

Some plant variables showed a quadratic response at the dose of 20 t ha^{-1} of added residues (**RFM with MAC:** $\hat{y} = 0.68 + 0.099\ x - 0.003\ x^2$; $R^2 = 0.6934$; Pr/F = 164.121**; MP = 16.5 t ha^{-1}; **RV with MAC:** $\hat{y} = 0.98 + 0.170\ x - 0.0050\ x^2$; $R^2 = 0.9493$; Pr/F = 26.591**; MP = 17.0 t ha^{-1}; **RFM with SLU:** $\hat{y} = 0.70 + 0.084\ x - 0.002\ x^2$; $R^2 = 0.4199$; Pr/F = 37.059**; **RV with SLU:** $\hat{y} = 1.56 + 0.123\ x - 0.005\ x^2$; $R^2 = 0.7244$; Pr/F = 23.995**; MP = 12.3 t ha^{-1}). The maximum points (satisfactory doses) of RFM and RV were 16.5 and 17.0 t ha^{-1}, respectively, with the addition of 20 t ha^{-1} of MAC and 12.3 and 21 t ha^{-1}, respectively, with the addition of 20 t ha^{-1} of SLU. The behavior observed for these two variables indicates that there is no need to incorporate doses higher than 21 t ha^{-1} into the soil, as SLU doses contribute most to increase RFM in the presence of 20 t ha^{-1} of MAC and vice versa, a behavior that is also valid for RV.

Table 5
Mean values for phosphorus (P), soil reaction (pH), magnesium (Mg^{2+}) and base saturation (V%), F values, regression equations, coefficient of determination (R^2), and maximum point (MP – t ha^{-1}) in the unfolding of the interaction between doses of aquatic macrophyte (MAC) x sewage sludge (SLU) for *Stylosanthes capitata*

Doses	MAC (t ha^{-1})	R^2	F Values	MP	SLU (t ha^{-1})	R^2	F Values	MP
	----- P (mg kg^{-1}) -----				---- P (mg kg^{-1}) ----			
0	$\hat{y} = 4.14 + 0.70x - 0.02x^2$	0.5222	7.830**	17.5	$\hat{y} = 5.68 + 0.51x$	0.8581	63.647**	
10	$\hat{y} = 14.34 - 0.22x$	0.9762	12.114**		$\hat{y} = 10.57 + 0.27x$	0.6996	17.467**	
20	$\hat{y} = 15.82 - 0.15x$	0.7637	5.440 *		$\hat{y}^{ns}$	-	-	
30	$\hat{y} = 20.74 - 0.68x - 0.02x^2$	0.2837	7.154**	17.0	$\hat{y} = 6.06 + 0.37x$	0.8156	34.590**	
	-------- pH ---------				-------- pH --------			
0	$\hat{y} = 6.52 + 0.01x$	0.4136	6.156 *		$\hat{y} = 6.33 + 0.09x + 0.002x^2$	0.1000	14.127**	22.8
10	$\hat{y}^{ns}$	-	-		$\hat{y} = 7.00 – 0.04 + 0.001x^2$	0.7530	4.192 *	
	- Mg^{2+} (mmolc kg^{-1}) -				- Mg^{2+} (mmolc kg^{-1}) -			
0	$\hat{y}^{ns}$	-	-		$\hat{y} = 8.18 + 0.59x$	0.9986	12.775**	
10	$\hat{y} = 12.13 – 0.09x$	0.8639	4.005 *		$\hat{y}^{ns}$	-	-	
20	$\hat{y} = 12.51 - 0.40x + 0.011x^2$	0.8405	4.691 *	18.0	$\hat{y}^{ns}$	-	-	
	-------- V (%) --------				-------- V (%) --------			
0	$\hat{y} = 61.17 + 1.36x - 0.0224x^2$	0.8761	21.145**	30.2	$\hat{y} = 65.66 + 0.78x$	0.6996	27.698**	
10	$\hat{y}^{ns}$	-	-		$\hat{y} = 77.38 + 0.31x$	0.7751	4.357 *	

Means followed by the same letter, in the columns do not differ significantly by Tukey test ($p \leq 0.05$). **, * and ^{ns} represent significant values for $p \leq 0.01$, $p \leq 0.05$, and non significant, respectively.

Table 6

Mean values of plant height (HEI), shoot fresh (SFM) and dry mass (SDM), root fresh (RFM) and dry mass (RDM), root volume (RV), F values, overall mean, coefficient of variation (CV), regression equations, and coefficient of determination (R^2) for *Stylosanthes capitata* for treatments (doses (t ha^{-1}) of sugarcane bagasse ash-ASH, aquatic macrophytes-MAC, and sewage sludge-SLU)

Source of Variations	HEI (cm)	SFM	SDM	RFM	RDM	RV (cm^3)		HEI (cm)	SFM	SDM	RFM	RDM	RV (cm^3)
		------- (g)	-------	-------	-------				------- (g)	-------	-------	-------	
	F Values						MAC (t ha-¹)	Means					
ASH	37.615**	15.702**	15.553**	60.968**	38.000**	14.463**	0	3.2	1.0	0.9	0.8	0.8	1.1
MAC	12.416**	4.977 *	5.167**	19.864**	20.282**	15.133**	10	3.9	1.2	1.1	0.9	0.9	1.6
SLU	32.238**	9.662**	8.101**	48.283 *	36.170**	10.194**	20	4.4	1.2	1.0	1.1	0.9	1.8
ASH x MAC	9.891**	2.102^{ns}	1.817^{ns}	14.233**	8.445**	3.881 *	30	4.8	1.4	1.2	0.9	0.9	2.0
ASH x SLU	0.707^{ns}	2.091^{ns}	1.473^{ns}	22.048**	12.251**	3.273 *	SLU (t ha-¹)	Means					
MAC x SLU	4.640**	1.012^{ns}	0.829^{ns}	25.303**	18.416**	4.384**	0	4.9	1.3	1.1	0.9	0.9	1.8
Overall eans	4.1	1.2	1.0	0.9	0.9	1.6	10	4.5	1.2	1.1	0.8	0.8	1.7
CV (%)	27	37	31	14	10	34	20	4.5	1.4	1.2	1.1	1.0	1.8
ASH	Means						30	2.4	0.8	0.8	0.8	0.8	1.2
With	4.7 a	1.3 a	1.2 a	1.0 a	0.9 a	1.8 a							
Without	3.5 b	1.0 b	0.9 b	0.8 b	0.8 b	1.4 b							

Means followed by the same letter, in the columns, do not differ significantly by Tukey test ($p \leq 0.05$). **, * and ^{ns} represent significant values for $p \leq 0.01$, $p \leq 0.05$, and non significant, respectively. **Significant regression equations for doses of MAC: HEI** ($\hat{y}$=3..27 + 0..05 x; R^2= 0..9905; Pr/F=36..893**), SFM ($\hat{y}$=0..99 + 0..01 x; R^2=0..8921; Pr/F=13.320**), **SDM** ($\hat{y}$= 0.90 + 0.01 x; R^2=0.8817; Pr/F=13.667**), **RFM** ($\hat{y}$=0.78 + 0.02 x – 0.0006 x2; R^2=0.8216; Pr/F=25.833*, Maximum point (MP)=19.0 t ha^{-1}), **RDM** ($\hat{y}$=0.76 + 0.14 x – 0.0004 x^2; R^2=0.8260; MP =23.076**; **MP** =17.6 t ha^{-1}), **RV** ($\hat{y}$=1.18 + 0.028; R^2=0.9434; Pr/F= 42.829**). **Significant regression equations for doses of SLU: HEI** ($\hat{y}$=4.74 + 0.056 x – 0.0043 x^2; R^2=0.9131; Pr/F=19.169**; **MP**=6,5 t ha^{-1}), **SFM** ($\hat{y}$=1.21 + 0.028 x – 0.0013 x^2; R^2=0.7929; Pr/F=11.783**; **MP**=10.7 t ha^{-1}), **SDM** ($\hat{y}$=1.16 – 0.008 x; R^2=0.4370; Pr/F= 10.619*), **RFM** ($\hat{y}$=0.88 + 0.019 x – 0.0007 x^2; R^2=0.2937; Pr/F=37.059**; **MP**=13.4 t ha^{-1}), **RDM** ($\hat{y}$=0.83 + 0.010 x – 0.0004 x^2; R^2=0.3629; Pr/F=31.362**; MP=13 t ha^{-1}), **RV** ($\hat{y}$=1.87 – 0.018 x; R^2=0.5825; Pr/F=17.814**). Pr/F = Probability of F; MP = maximum point.

Table 7

Mean values of root fresh (RFM) and dry mass (RDM), root volume (RV), and plant height (HEI) for unfolding of the interaction between doses of sugarcane bagasse ash (ASH) and aquatic macrophytes (MAC), and means value of root fresh (RFM) and dry mass (RDM) and root volume (VR) for unfolding of the interaction between doses of ASH and sewage sludge (SLU) for *Stylosanthes capitata*, as well as F values, regression equations, and coefficient of determination (R^2)

ASH	0 (t ha^{-1})	10 (t ha^{-1})	20 (t ha^{-1})	30 (t ha^{-1})	F Values	0 (t ha^{-1})	10 (t ha^{-1})	20 (t ha^{-1})	30 (t ha^{-1})	F Values
	Doses of MAC (t ha^{-1})					**Doses of SLU (t ha^{-1})**				
	-------------------- RFM (g) --------------------					-------------------- RFM (g) --------------------				
With	0.08 a	1.00 a	1.25 a	0.98 a	33.282**	1.03 a	0.87 a	1.37 a	0.75 a	67.590**
Without	0.80 a	0.79 b	0.85 b	0.85 a	0.81 ^{ns}	0.84 b	0.81 a	0.89 b	0.76 a	2.742 *
F Values	0.91 ^{ns}	20.49**	75.91**	7.17**		16.433**	1.548 ^{ns}	109.116**	0.016 ^{ns}	
	-------------------- RDM (g) --------------------					-------------------- RDM (g) --------------------				
With	0.77 a	0.89 a	1.03 a	0.87 a	25.760**	0.89 a	0.84 a	1.07 a	0.75 a	44.553**
Without	0.77 a	0.79 b	0.83 b	0.83 a	2.97 *	0.83 b	0.78 b	0.84 b	0.75 a	3.869 *
F Values	0.002 ^{ns}	18.496**	42.387**	2.450 ^{ns}		5.331 *	4.085 *	65.330**	0.007 ^{ns}	
	-------------------- RV (cm^3) --------------------					-------------------- RV (cm^3) --------------------				
With	1.25 a	2.02 a	1.93 a	1.95 a	7.015**	2.09 a	1.84 a	2.11 a	1.10 a	12.123**
Without	0.95 a	1.51 b	1.57 a	2.01 a	11.099**	1.47 b	1.56 a	1.46 b	1.19 a	1.344 ^{ns}
F Values	2.459 ^{ns}	20.139**	3.418 ^{ns}	0.089 ^{ns}		10.206**	2.227 ^{ns}	11.611**	0.238 ^{ns}	
	-------------------- HEI (cm) --------------------									
With	3.74 a	5.32 a	4.90 a	4.75 a	5.755**					
Without	2.67 b	2.47 b	3.80 b	4.93 a	16.552*					
F Values	7.355**	52.013**	7.728**	0.192 ^{ns}						

Means followed by the same letter, in the columns do not differ significantly by Tukey test ($p \leq 0.05$). **, * and ^{ns} represent significant values for $p \leq 0.01$, $p \leq 0.05$, and non significant, respectively. **Significant regression equations for doses of MAC: RFM with ASH** ($\hat{y}$=0.761 + 0.045 x - 0.001 x²; R^2=0.8538; Pr/F=55.271**), **RDM with ASH** ($\hat{y}$=0.755 + 0.025 x – 0.001 x²; R^2=0.8761; Pr/F=44.656**), **RDM without ASH** ($\hat{y}$=0.765 + 0.002 x; R^2=0.7433; Pr/F=6.617*), **RV with ASH** ($\hat{y}$=1.482 + 0.020 x; R^2=0.5253; Pr/F=11.055**, maximum point (MP)=19.0 t ha^{-1}), **RV without ASH** ($\hat{y}$=0.878 + 0.036 x; R^2=0.9770; Pr/F=35.168**; MP=17.6 t ha^{-1}), **ALT with ASH** ($\hat{y}$=3.854 + 0.155 x – 0.004 x²; R^2=0.8050; Pr/F=9.488**), **ALT without ASH** ($\hat{y}$=2.252 + 0.081 x; R^2=0.8482; Pr/F=42.118**). **Significant regression equations for doses of SLU: RFM with ASH** ($\hat{y}$=0.937 + 0.032 x – 0.001 x²; R^2=0.2686; Pr/F=49.695**; MP=6.5 t ha^{-1}), **RDM with ASH** ($\hat{y}$=0.851 + 0.019 x – 0.001 x²; R^2=0.3760; Pr/F=45.502**; MP=10.7 t ha^{-1}), **RDM without ASH** ($\hat{y}$=0.814 + 0.002 x – 0.001 x²; R^2=0.4060; Pr/F=3.333**; MP=13.4 t ha^{-1}), **RV with ASH** ($\hat{y}$=2.191 – 0.027 x; R^2=0.5393; Pr/F=19.613**).

Conclusions

The residues sugarcane bagasse ash, sewage sludge, and aquatic macrophytes increased the availability of calcium in the soil by 59%, thereby improving its chemical aspect. Sewage sludge notably enhanced Ca^{2+}, P, OM, and Mg^{2+} content in the soil. The growth in height of *S. capitata* was higher with the application of 20 t ha^{-1} of both sewage sludge and aquatic macrophytes. Height, shoot fresh mass, root dry mass, and root volume were higher in the presence of 20 t ha^{-1} of sewage sludge. The residues ash, sewage sludge, and aquatic macrophytes collectively contributed to soil recovery and initial growth of *S. capitata.*

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