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Sewage sludge-based organomineral fertilizer improves phosphorus efficiency in *Urochloa brizantha*

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ABSTRACT: Sewage sludge (SS) from wastewater treatment has reasonable phosphorus (P) levels, which could be used as fertilizer in agriculture. However, SS-P content is lower than mineral fertilizers, which limits its operational application. The blend of organic and mineral material can increase the P content, formulating organomineral fertilizers (OMF) with higher P levels, enabling agricultural use. This study aimed to assess the agronomic efficiency and residual effect of organomineral fertilizers derived from SS as phosphorus sources for *Urochloa brizantha*. A greenhouse pot experiment was conducted to evaluate the successive cultivation of *U. brizantha* over eight cycles, with the following treatments: SS organic compost (SSC) powder; SSC pelletized (SSP), SSC+MAP pelletized (S+MAP) and SSC+AshDec® pelletized (S+ASD); AshDec® powder (ASD), monoammonium phosphate (MAP) and a control (no P). In each *Urochloa* cycle, height, tillering, shoot dry mass (SDM), and leaf P were evaluated. After eight cycles, the soil was subjected to P fractional analysis. Our results showed that tillering was higher in all treatments with P compared to control (No P). Shoot dry mass production in the first cycle was higher with S+MAP (21.8 g pot^{-1}) than MAP (17.5 g pot^{-1}), and after eight cycles, the accumulated SDM of all treatments (>140 g pot^{-1}) was superior to MAP (132 g pot^{-1}), except for S+ASD (118 g pot^{-1}). No significant difference in plant height was observed. Total P uptake was higher in the treatments with recycled sources, however, plants fertilized with S+MAP accumulated more P during establishment, while SSC, SSP, and ASD promoted higher accumulation during 4 to 6 cycles. After eight cycles, soil labile P content was higher in treatments with OMFs compared to mineral sources, indicating a residual effect of organomineral fertilization. These results showed that SSC-derived OMFs are more efficient than conventional fertilizers if mixed with soluble mineral sources (MAP), but the same is not true with insoluble sources (ASD). Organomineral S+MAP can replace MAP, providing greater efficiency in forage establishment and a greater residual effect.

Keywords: organic waste, biosolid, pelletized organomineral, P availability, P use efficiency.

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INTRODUCTION

Waste generation is an inevitable consequence of human activities, closely linked to economic growth and urbanization. Inadequate waste management and disposal practices pose significant risks to environmental integrity and public health (Kaza et al., 2018). Wastewater treatment is essential to ensuring that water meets the discharge standards established by environmental regulatory agencies. During the treatment process, sewage sludge is generated, characterized by its high nutrient content and organic matter that could be used in agriculture (Singh and Agrawal, 2008; Nascimento et al., 2018), and thus, reduce the pressure on rock mining for the fertilizer industry (Cordell et al., 2009; Ashley et al., 2011). However, sewage sludge (SS) generated in this process is mainly disposed of in landfills in Brazil.

The use of biosolids in agriculture is already a reality in some European countries, South Africa, Australia, India, Japan, and the United States, but it is not yet widespread in Brazil (Sharma et al., 2017). Before application in agriculture SS requires some pathogen reduction treatment, and one of the most economical and environmentally low-risk methods is composting (Waqas et al., 2018), which also reduces the bioavailability and content of potentially toxic elements (PTEs) (Moretti et al., 2015). Incineration is another treatment method, even more effective in eliminating organic contaminants (Hušek et al., 2022). In this process, the ashes generated have around 15-20 % of P_2O_5, the same order of the concentrated phosphate rocks (25-36 %), but they also have a considerable content of PTEs. An evolution of this incineration is the thermochemical treatment method to produce AshDec®, which can reduce PTEs and increase P bioavailability (Adam et al., 2009; Hermann and Schaaf, 2019).

Phosphorus (P) is one of the main nutrients present in SS that needs to be applied in large quantities to meet P fertilization recommendations due to lower concentrations in SS than conventional fertilizers, and it also poses challenges in the storage and transportation of the final products (van der Kooij et al., 2020). The P contained in SS is present in organic forms or as Fe and Al phosphates that are sparingly soluble in water that need be mineralized (O'Connor et al., 2013; Kominko et al., 2021). Thus, one strategy to enhance its competitiveness relative to conventional fertilizers is to blend it with concentrated soluble sources.

Organomineral fertilizers (OMFs) are blends of organic and mineral fertilizers that supply nutrients and organic matter to the soil. They are considered slow-release fertilizers, allowing greater synchronization between nutrient availability and plant demand (Kominko et al., 2017). Application of OMFs is promising for enhancing P uptake efficiency by plants. Conventional phosphate fertilizers immediately solubilize P in the soil solution, which promotes losses through erosion, runoff, or fixation (which mainly occurs in weathered soils, where clays can adsorb P with practically irreversible high-energy bonds), thus reducing its availability to plants (Antille et al., 2014; Sakurada et al., 2016, 2019; Kominko et al., 2017).

Several studies using OMFs from various residues showed more efficiency than conventional fertilizers in wheat, barley, rapeseed, and forage corn (Deeks et al., 2013), beans (Deeks et al., 2013; Mumbach et al., 2020), sunflower (Kominko et al., 2021), corn (Sakurada et al., 2016; Mumbach et al., 2020; Kominko et al., 2021), soybeans (Prates et al., 2020; Rodrigues et al., 2021), which were also observed in OMFs derived from sewage sludge (Rigueiro-Rodríguez et al., 2010; Prates et al., 2020; Rodrigues et al., 2021; Kominko et al., 2022). However, research evaluating the residual effect of OMFs derived from sewage sludge in tropical conditions is still in the early stages.

Due to the wide range of combinations of SS with inorganic materials, proportions, binding agents, and physical forms, further research is needed to evaluate the agronomic efficiency of OMFs and identify the combinations, management practices, and crops for which each product is best suited. Additionally, experiments focusing on P depletion in successive crops can provide insights into how P is released from OMFs and their residual effect on the soil. Therefore, this study could promote SS use in agriculture, which is also one of the strategies outlined in the National Fertilizer Plan to reduce Brazil dependence on imported fertilizers (Brasil, 2023).

We hypothesized that OMFs supply P to the soil in bioavailable forms for a longer period than soluble mineral fertilizers, thus enhancing the efficiency of phosphate fertilization and potentially replacing mineral fertilizers entirely or partially in forage production. Our objective was to analyze the agronomic potential and residual effect of OMFs using composted sludge as an organic matrix, combined with two inorganic P sources: one synthetic (MAP) and another derived from P recovery (AshDec®). Therefore, a greenhouse experiment was conducted with eight successive cycles of *Urochloa brizantha*, a perennial forage widely cultivated in the tropics, with the ability to recycle soil P.

MATERIALS AND METHODS

Production and characterization of organomineral fertilizers

The organic compound was produced through composting sewage sludge with tree pruning and grass clippings. The composting process took place at the Bela Vista Wastewater Treatment Plant, Piracicaba, São Paulo (SP), Brazil, by the concessionaire responsible Águas do Mirante in partnership with the São Paulo Agency for Agribusiness Technology (APTA) and the Luiz de Queiroz College of Agriculture (ESALQ).

Sewage sludge compost (SSC) exhibited the following characteristics: moisture content – 38.1 %; total solids, volatile solids, and fixed solids of 59.6, 41.9, and 17.7 %, respectively; electrical conductivity of 3,020 μS cm^{-1}; 36.2 % of C, 2.6 % of N, C/N equal to 13.9; 1130 $mmol_c$ kg^{-1} of CEC, and 3.4×10^2 MPN g^{-1} of *E. coli* in TS (most probable number per gram of total solids), and absence of *Salmonella* sp. These observed parameters and the content of potentially toxic elements (Table S1) comply with the criteria established in Brazilian legislation by the National Council Environment, Resolution 498/2020 to be applied as organic fertilizer in agricultural soils (Brasil, 2020).

The ASD used in the experiment was produced in Germany by the Federal Institute for Materials Research and Testing (BAM) in collaboration with the company Outotec. To produce pelleted organomineral fertilizers, the mass/mass ratio was 70 % SSC and 30 % inorganic material (ASD or MAP). The materials were ground, mixed, moistened with water, and pelletized. After drying the pellets at room temperature, the chemical composition of the fertilizers was determined according to the Manual of Chemical Analysis of Soils, Plants, and Fertilizers (Silva, 2009) (Table 1). Further details on the production and physicochemical characterization of the pellets produced can be accessed in Espinoza et al. (2023).

Table 1. Nutrient content in phosphate fertilizer sources used as treatments

Fertilizers	N	K_2O	Ca	Mg	Na	P_2O_5 total	P_2O_5 H_2O	P_2O_5 HCi	P_2O_5 NAC
	%								
SSC	3.7	1.1	3.1	0.6	0.1	2.5	0.4	2.2	2.3
SCP	3.7	1.1	3.1	0.6	0.1	2.5	0.4	2.2	2.3
S+MAP	5.9	0.8	2.2	0.4	0.1	17.3	13.5	17.1	17.2
S+ASD	2.6	0.6	4.4	0.8	3.3	6.8	0.5	6.2	6.4
ASD	-	0.3	9.5	1.5	11.0	16.6	0.7	15.6	15.8
MAP	11.0	-	-	-	-	52.0	44.0	51.8	52.0

P_2O_5 HCi: soluble in citric acid 2 %; NAC: neutral ammonium citrate; SSC: organic sewage sludge compost; SCP: pelletized organic sewage sludge compost; S+MAP: organic sewage sludge compost + MAP; S+ASD: organic sewage sludge compost + AshDec®; ASD: AshDec®; MAP: monoammonium phosphate.

Experimental design and treatments

The soil used in the experiment was collected from the surface layer of 0.00-0.20 m in a Ferralsol (IUSS Working Group WRB, 2015), classified as Latossolo Vermelho Amarelo Distrófico in the Brazilian system (Santos et al., 2018), located in a pastureland area, in Piracicaba, SP (22° 42' S and 47° 37' W). Soil was air-dried, sieved through a 2 mm sieve, and sampled for chemical analysis (Silva, 2009) and texture. Soil composition was 170 g kg^{-1} clay, 740 g kg^{-1} sand and 9 g kg^{-1} silt; chemical parameters were: pH($CaCl_2$) 4.6; organic matter: 14 g dm^{-3}; Ca^{2+}: 4 $mmol_c$ dm^{-3}; Mg^{2+}: 3 $mmol_c$ dm^{-3}; K^+: 1 $mmol_c$ dm^{-3}; Al^{3+}: 2 $mmol_c$ dm^{-3}; H+Al: 22 $mmol_c$ dm^{-3}; cation exchange capacity (CEC): 30 $mmol_c$ dm^{-3}; base saturation: 27 %; Al saturation: 20 %; and P <6 mg dm^{-3}, which is considered low according to Cantarella et al. (2022). The $CaCO_3$ and MgO were incorporated one day before *Urochloa* sowing to raise the levels of Ca^{2+} and Mg^{2+} to 20 and 8 $mmol_c$ dm^{-3}, respectively.

The experiment was conducted in a greenhouse at the Soil Science Department, ESALQ/USP (Piracicaba, SP), using a randomized complete block design with four replications, with the treatments being composed of P sources: 1) sewage sludge organic compost powder (SSC); 2) SSC pelletized (SCP); 3) organominerals SSC + MAP pelletized (S+MAP); 4) SCP + AshDec® pelletized (S+ASD); 5) AshDec® powder (ASD); 6) granulated monoammonium phosphate (MAP); and 7) control (No-P). The P sources were incorporated into the total mass of 5.5 kg of soil per pot at a rate of 60 mg kg^{-1} of P, based on the total P of each source. The soil was moistened and, the next day, sown with 30 seeds of *Urochloa* per pot at a depth of 1 cm. Thinning was done after 10 days to establish a population of 6 plants per pot. Soil moisture was maintained at around 70 % of its maximum water holding capacity (WHC), using deionized water for irrigation.

To ensure that only P was the limiting nutrient, topdressing fertilization was applied 20 days after sowing with macro and micronutrients, and maintenance fertilization was applied 7 days after each cut. In all cycles were applied 100 mg kg^{-1} of N and K, in the forms of NH_4NO_3 and K_2SO_4, while micronutrients were applied in the 1st, 3rd and 5th cycles, corresponding to 0.5 mg kg^{-1} of B (H_3BO_3), 2 mg kg^{-1} of Zn ($ZnSO_4$) and 2 mg kg^{-1} of Mn ($MnSO_4.H_2O$). In the 6th cycle, 1 mg kg^{-1} of B (H_3BO_3) and Cu ($CuSO_4$), and 60 mg kg^{-1} de Mg (MgO) were also applied.

Analysis of plant growth

Urochloa development was evaluated by the number of tillers, stem height, and shoot dry mass (SDM) at each cutting cycle. The first cutting was performed 47 days after sowing, and subsequent cuttings were done 30 days after the previous one. For dry mass determination, the plants were cut 5 cm above the ground, placed in paper bags, and left in a forced-air oven at 65 °C until constant weight. The dried material was ground in a mill with a 1 mm sieve for chemical analysis of nutrients and heavy metals in plant tissue, by nitric-perchloric digestion followed by determination using inductively coupled plasma atomic emission spectroscopy (ICP), and N by sulfuric digestion and colorimetric determination (Silva, 2009). The shoot P and nutrients accumulated (mg pot^{-1}) at each harvest were obtained by multiplying the P content in the leaf (mg kg^{-1}) by the SDM (g).

With the aim of measuring the agronomic efficiency of the different alternative P sources compared to the conventional source (MAP), the Agronomic Efficiency Index (AEI; Equation 1) was used.

$$\text{AEI} = [(Y_i - Y_0) / (Y_{MAP} - Y_0)] \times 100 \qquad \text{Eq. 1}$$

in which: Y_i corresponds to the dry biomass yield of treatments with recycled sources; Y_0 is the yield of the control; and Y_{MAP} is the yield of the treatment with the conventional source MAP.

Finally, the P absorption efficiency (PAE; Equation 2) by the plants was calculated for each source in relation to the amount of P applied to the soil (60 mg kg^{-1}).

$$PAE\ (\%) = \left(P_{accumulated} / P_{applied}\right) \times 100 \qquad \text{Eq. 2}$$

Soil analysis

In the 4th and 8th cycles, soil samples of approximately 300 g each were collected for chemical analysis of elements (Silva, 2009) (Table S2) and chemical fractionation of P, performed using the method of Hedley et al. (1982) with modifications from Gatiboni et al. (2007). In this method, P is sequentially extracted from soil samples with 0.5 g using different chemical extractants, and its content is determined by the molybdate blue method (Murphy and Riley, 1962); the results were grouped by lability as follows: Pi and Po labile (extracted by anion exchange resin (Pi-AER) and 0.5 mol L^{-1} $NaHCO_3$ (Pi and Po-bic)); Pi and Po moderately labile (0.1 mol L^{-1} NaOH (Pi and Po) and 0.1 mol L^{-1} HCl (Pi)); and Pi and Po non-labile (0.5 mol L^{-1} NaOH (Pi and Po)), and residual Pi extracted by 0.1 g soil digestion, with H_2SO_4 + H_2O_2. The Po was determined by the difference between the total P of the $NaHCO_3$, NaOH 0.1 and 0.5 mol L^{-1} extracts (obtained by digesting the extracts with H_2SO_4 + $(NH_4)_2S_2O_8$) and the Pi.

Statistical analysis

To check the model assumptions, the data were analyzed for residual normality using the Shapiro-Wilk test ($p<0.05$) and variance homogeneity using the O'Neill-Mathews test ($p<0.05$). Then, mixed models with repeated measures in time ($p<0.05$) were applied to compare the P sources × cycles. Means were compared using the Tukey test ($p<0.05$). Statistical analyses were performed using the R software with the *nlme*, *emmeans* and *multcomp* packages.

RESULTS

Biometric parameters

In general, over the *Urochloa* crop cycles, there was minimal (1th, 2th, 3th and 7th cycles) or no significant difference (4th, 5th, 6th and 8th cycles) in plant high due to the application of P sources (Figure S1). Nevertheless, plants fertilized with P sources showed greater height than control (No-P) until the third cycle, as well as a greater tillering than the control in all cycles (Figure 1a). The sources OMFs composed of S+MAP and S+ASD promoted the same tiller production as their isolated mineral raw materials (MAP and ASD), across all cycles. In turn, treatments with SCC and SCP showed higher tillering than the soluble source MAP in the 5th and 6th cycles, and in the case of SCP, also in the 7th and 8th cycles.

Recycled sources provided higher accumulated SDM yield at the end of 8 cycles compared to the conventional MAP fertilizer (133 g pot^{-1}), except for S+ASD (122 g pot^{-1}) and ASD (145 g pot^{-1}), which achieved similar values (Figure 1b), what also reflected in AEI which is directly related to SDM yield (Figure 1d). Recycled sources were 10-20 % more efficient than conventional fertilizer (MAP), except for S+ASD, which showed agronomic efficiency similar to MAP, indicating the viability of using these fertilizers as an alternative to MAP in *Urochloa* cultivation. Nevertheless, the total or partial replacement of the use of soluble P sources with these alternative sources should be considered carefully, as there was variation in biomass yield between cycles (Figure 1a), demonstrating that the efficiency of these alternative sources in supplying P to the plants also varies over time.

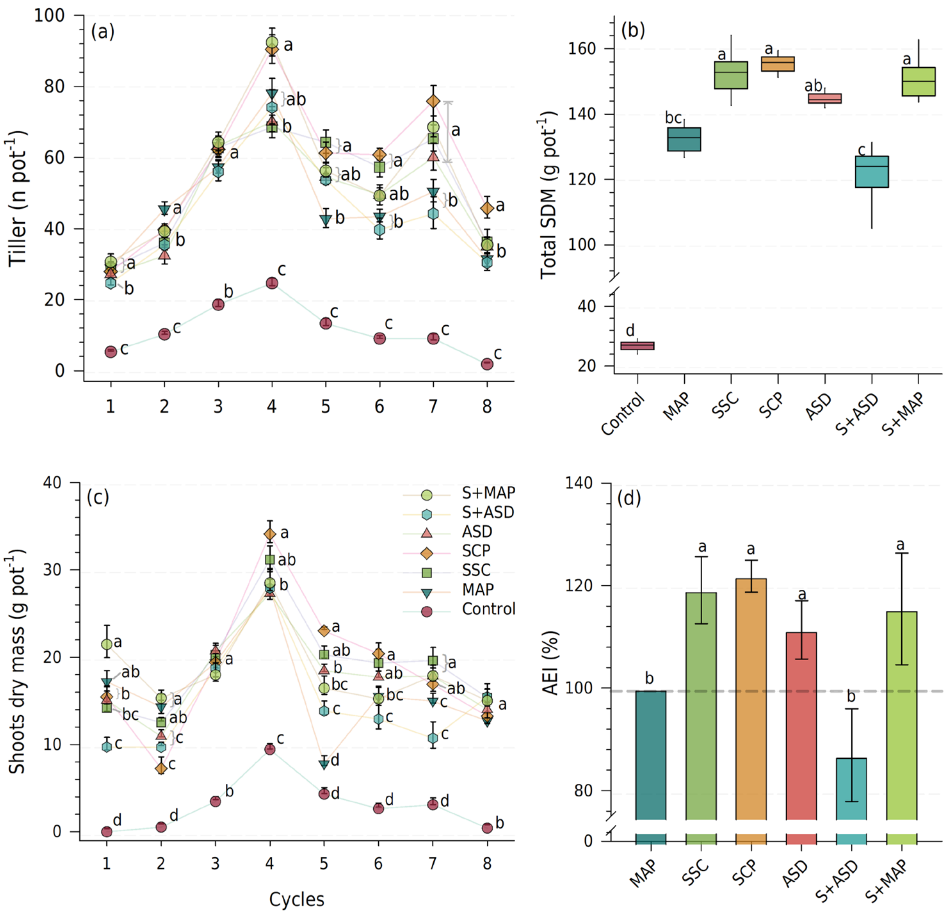

Figure 1. Phytometric parameters of *Urochloa*: number of tillers (a), total accumulated dry biomass of the aerial part (b), DM accumulated per cycle (c), and Agronomic efficiency index (d). SSC: sewage sludge compost; SCP: sewage sludge compost pelletized; S+MAP: organic compost + MAP; S+ASD: organic compost + AshDec®; ASD: AshDec®; MAP: monoammonium phosphate.

In terms of biomass production per cycle, the organomineral S+MAP exhibited similarities with its isolated raw materials (MAP and SCC). However, in the 1st cycle, S+MAP (21.8 mg pot^{-1}) surpassed SCC (15.8 mg pot^{-1}) and SCP (15.6 mg pot^{-1}), while in the 5th cycle, S+MAP yielded 53 % more than MAP. This outcome supports our hypothesis that the OMF has a greater residual effect and is more efficient than soluble phosphate fertilizers over the medium to long term (Figure 1c). Conversely, S+ASD failed to elicit higher biomass production than SCC, SCP, and ASD across all cycles and consistently yielded less biomass than these sources in several cycles. Notably, it fell short of the mineral source ASD by 33 % in the 1st, 5th, and 6th cycles. Between the two OMFs evaluated here, S+MAP outperformed S+ASD in the 1st (S+MAP = 21.8 g pot^{-1}; S+ASD = 10.1 g pot^{-1}) and 2nd cycles (S+MAP = 15.7 g pot^{-1}; S+ASD = 10.0 g pot^{-1}) and exhibited similar results in subsequent cycles.

Both powder and pelletized organic compost promoted a similar effect to MAP in SDM yield in most cycles, except in the 5th, 6th, and 7th where SCP was superior (Figure 1c). Physical forms of the compost did not differ in terms of SDM production, except in the 2nd cycle, in which SCP (12.9 g pot^{-1}) > SSC (7.6 g pot^{-1}).

P accumulated in shoot biomass

Overall, the highest accumulation of P in the aboveground biomass occurred in the 4th cycle, similar to SDM, and from this cycle onwards, there was a decrease in biomass P accumulation (Figure 2a and Figure S1b). Nevertheless, the highest amount of accumulated P occurred in the 1st cycle with the application of S+MAP (74.3 mg pot^{-1}), surpassing the source with the highest content of soluble P (MAP; 48.3 mg pot^{-1}). Moreover, S+MAP still promoted a higher accumulation of P than MAP by 27 and 64 % in the 4th and 5th cycles, respectively. This suggests that S+MAP made P available for a longer period than MAP, being this P absorbed more effectively by *Urochloa*, even in the early stages of the crop development.

The recycled sources had higher shoot biomass P than the control, being equal to or even higher than the conventional source (MAP) in all cycles, except for S+ASD in the 1st cycle (28.25 mg pot^{-1}), in which the exported amount was nearly half that of MAP (48.33 mg pot^{-1}). Furthermore, S+ASD was inferior to ASD in the 3rd cycle (28.5 *vs*. 41.7 mg pot^{-1}), to SSC in the 5th cycle (20.3 *vs*. 39.1 mg pot^{-1}), and to S+MAP in the 1st cycle (28.3 *vs*. 74.3 mg pot^{-1}).

The total accumulated P in the aboveground biomass was 20 to 33 % higher with recycled sources than with MAP (212.6 mg pot^{-1}), except for S+ASD (202.6 mg pot^{-1}) (Figure 2b). This suggests that pelletization of SSC with a poorly soluble mineral source like ASD was not advantageous, as P absorption by the plants was lower with S+ASD than with its isolated raw materials. In turn, plants fertilized with SSC and SCP accumulated P in the biomass similarly to MAP in most cycles, except in the 5th cycle, in which SSC and SCP > MAP (SSC = 23.3 mg pot^{-1}; SCP = 20.6 mg pot^{-1}; MAP = 8.2 mg pot^{-1}). This means that the amount of P supplied to *Urochloa* via SSC is equivalent to that of a soluble mineral fertilizer (MAP).

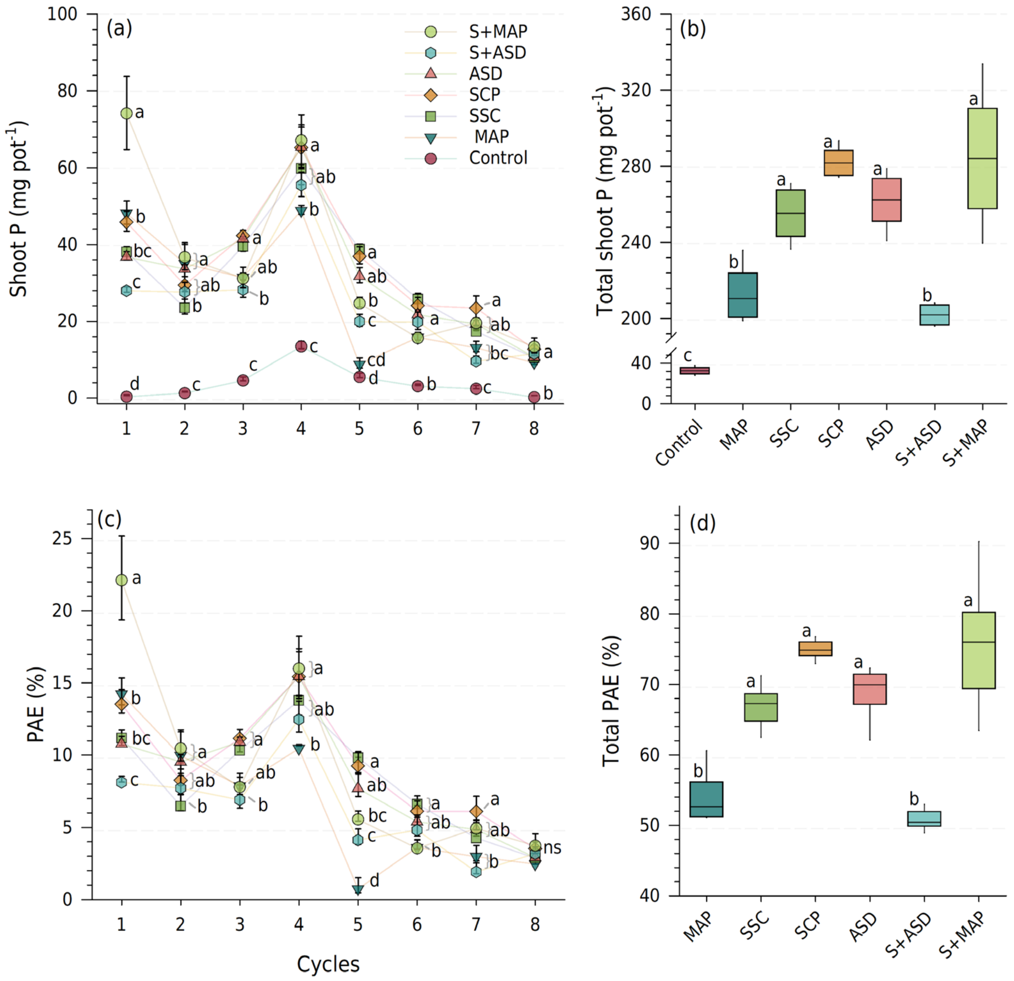

Figure 2. Accumulated P in aboveground biomass per cycle (a) and total (b), and P absorption efficiency per cycle (c) and total (d) of *Urochloa* under different P sources. SSC: sewage sludge compost; SCP: sewage sludge compost pelletized; S+MAP: organic compost + MAP; S+ASD: organic compost + AshDec®; ASD: AshDec®; MAP: monoammonium phosphate.

Although the recycled sources allowed for the absorption of P in quantities equivalent to or greater than MAP, the utilization of the applied fertilizer P (60 mg kg^{-1}) varied over time, as shown by the P absorption efficiency (PAE) (Figure 2c). With S+MAP, 22 % of the applied P was accumulated in the aboveground part in the first cycle, surpassing MAP (14 %), which may explain the higher SDM yield with S+MAP. On the other hand, approximately 17 and 16 % of the applied P via SSC and SCP was exported by the aboveground biomass considering the sum of the 5th and 6th cycles, while the utilization with MAP and S+MAP was only 5 and 10 %, respectively. Besides similar results in SDM and P in the aboveground biomass between SSC, SCP, and MAP, the PAE index was similar among them in the 1st cycle, demonstrating that SSC is a good source for *Urochloa*'s P demand during establishment and also in the long term, much like S+MAP (16 %) > MAP (11 %) in the 4th cycle. These results help demystify the fallacy that conventional fertilizers always provide greater P absorption by plants during crop establishment than organic ones.

Change in soil P dynamics

The soil P dynamics of distinct lability did not strongly vary with P sources and crop cycles, except for the reduction of non-labile P in the 4th and 8th cycles (Figure 3 and Table S4). However, when stratifying into Pi and Po, we observed significant changes, especially in labile P and non-labile Po.

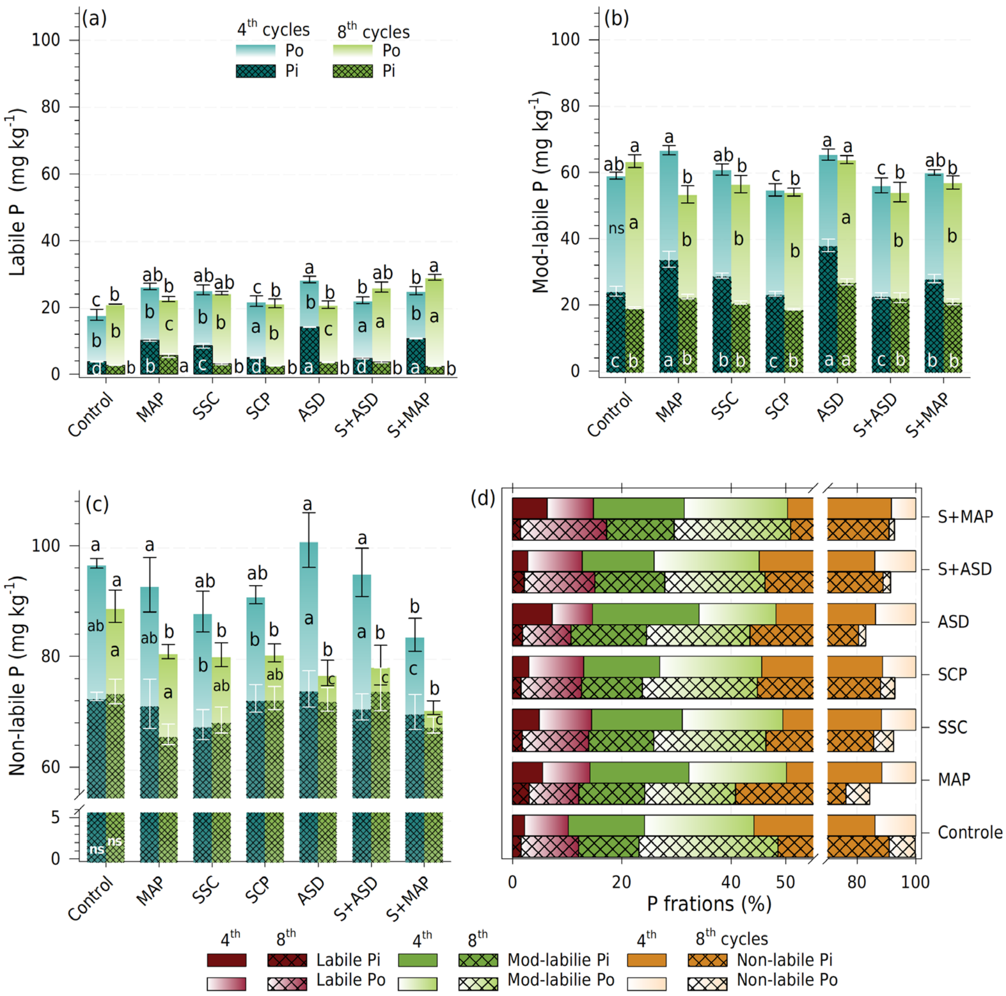

Figure 3. Changes in P fractions in the 4th and 8th cycles of *Urochloa* cultivation under distinct P sources. SSC: sewage sludge compost; SCP: sewage sludge compost pelletized; S+MAP: organic compost + MAP; S+ASD: organic compost + AshDec®; ASD: AshDec®; MAP: monoammonium phosphate.

In the 4th cycle, the highest levels of labile Pi were observed with ASD, S+MAP, and MAP (14, 11, and 10 mg kg^{-1}, respectively; Figure 3a), hence, they showed the greatest reductions in labile Pi (~72 %; p = 0.001) between the 4th and 8th cycles (Figure 3a and Table S4). Despite these reductions, the total labile P was buffered by an increase in labile Po, mainly in the organomineral sources (S+MAP and S+ASD, with increases of 86 and 29 % from the 4th to the 8th cycle) and SSC (+27 %) (Table S4). This increase in Po was not significant for the other sources, except for the control with a 30 % increase. After eight cycles of *Urochloa* cultivation, the sources containing sewage sludge compost (S+MAP, S+ASD, and SSC; p= 0.0010) showed the highest levels of total labile P (29, 26, and 24 mg kg^{-1}, respectively), except when pelletized (SCP).

There were no significant changes in total mod-labile P between cycles (Table S4) except for a reduction with MAP (-20 %, p = 0.0001; Figure 3b). Nonetheless, in the 4th cycle, only SCP and S+ASD were inferior to the control, while in the 8th cycle, only ASD was similar. The highest levels of mod-labile Pi were observed in the 4th cycle, especially with mineral sources (MAP and ASD). In the 8th cycle, all sources except ASD (27 mg kg^{-1}) showed mod-labile Pi similar to the control (~20 mg kg^{-1}). From the 4th to the 8th cycle, the depletion of this fraction was similar for all sources (~21 mg kg^{-1}; p = ~0.0017), except for S+ASD, which did not differ (p = 0.777, Table S4). In mod-labile Po, sources did not differ in the 4th cycle, but in the 8th cycle, ASD did not differ from the control; nonetheless, both increased Po by ~31 % (p = 0.0035) from the 4th to the 8th cycle.

The greatest depletions of P occurred in total non-labile P (often reported as stable P in the soil), mainly with ASD and S+ASD (-24 and -18 %), followed by SCP and MAP (~-11 %) (Figure 3c). These responses were due to the strong depletion of non-labile Po, which was greater in ASD and S+ASD, reaching up to -21 mg kg^{-1} (or -82 %), followed by S+MAP, SCP, and SSC with -78 %, -57 %, and -42 %, respectively. The control showed a similar response, although with a smaller effect size (-35 %). Non-labile Pi was not influenced by sources or cultivation cycles (p = 0.883; Table S4), however, there was a reduction of up to -20 % in residual P between cycles, but this was buffered by the NaOH 0.5 mol L^{-1} Pi fraction (Table S3).

These changes altered the distribution of P fractions (Figure 3d). The greatest depletions in total soil P occurred for ASD and MAP, while depletions were similar in sources derived from SSC (~-8 %). Overall, the proportion of the labile pool was 13 % of the total P, regardless of cycle or source, although with strong variations between Pi and Po of this fraction. This trend was also observed in the proportion of mod-labile P, at 33 %. As for non-labile P, there was a general reduction from 52 to 45 % from the 4th to the 8th cycle, with greater responses with ASD, due to the reduction in Po between cycles (Figure 3c).

DISCUSSION

Urochloa biometric parameters

Our results suggest that plant height and tillering were initially more influenced by soil P availability regardless of the P source. However, due to successive cuts in the aboveground biomass, growth mechanisms of *Urochloa* become more determinant, resulting in little difference between P sources (Figure S1a). This occurs because forage defoliation activates compensatory growth mechanisms, such as the translocation of carbohydrates stored in the roots to the leaves and the promotion of meristem growth, resulting in tiller growth (Ferraro and Oesterheld, 2002; Casagrande et al., 2010). Other authors also found no difference between P sources in the height growth and tillering of *Urochloa* after successive cuts. Dias et al. (2015) evaluated the tillering of this species over three cycles. They found no difference between applying single superphosphate or reactive natural phosphate, although tillering was higher in fertilized soil compared to the control. Similarly, Passos et al. (1997) found no difference using triple superphosphate, magnesium thermophosphate, and natural phosphate from Araxá with and without partial acidulation over six cuts. Rezende et al. (2011) found no difference in plant tillering with P application at different stages of cultivation, being superior only to the control. These results support the essential role of P in the initial development of forages, acting directly on root growth and tillering (Barcelos et al., 2011), although for the tillering of this species the P source is less determinant.

When comparing to conventional fertilizer, the OMF S+MAP promoted similar SDM production, even a bit superior in the 5th cycle, along with higher AEI over eight crop cycles. The greater residual effect and better yield may be attributed to the fact that MAP rapidly releases P into the soil at the early stage of the crop, favoring P immobilization in the soil through processes of adsorption and precipitation, thereby reducing P availability to plants over the time (Santos et al., 2009; McLaughlin et al., 2011; Sakurada et al., 2016). Meanwhile, in the OMF, soluble P is protected by the organic matrix, requiring more time to be released into the soil, which may better synchronize nutrient release with crop demand (Kominko et al., 2017).

On the other hand, the mixture of SSC with a less soluble source, ASD, resulted in lower SDM yield, especially in early crop stages, and also lower AEI resultant from the raw materials. This may have occurred due to the limitation in P availability inherent in this organomineral. In a leaching column experiment to evaluate P dynamics in soil fertilized with these same sources, Espinoza et al. (2023) observed that even in the presence of citric acid, S+ASD solubilized only 42 % of the total P, while the other sources solubilized more than 85 %.

The higher biomass production provided by SSC and SCP in the intermediate cycles (from 4th to 6th cycle) may be related to the time required for organic material mineralization for the release of this P into the soil. Studies indicate that a large part of the P in sewage sludge is in the inorganic form (Houben et al., 2019), which may have reflected in good P availability for plants in the initial cycles as well, where these sources provided SDM equivalent to MAP. These results are consistent with long-term studies on three forage species in forest livestock systems fertilized with SSC and pelletized sludge, which it was observed similar results to mineral fertilization (Rigueiro-Rodríguez et al., 2010) and higher biomass production of *U. decumbens* with sewage sludge application than with mineral fertilizer (Campos and Alves, 2008).

The gradual reduction and more homogeneous results of SDM yield in the last cycles also suggest that as the P supplied by fertilization is depleted, the physiological mechanisms of plants to utilize soil P residual become more determinant. Additionally, it is necessary to consider that the lack of P replenishment in the soil resulted in a reduction in leaf P content (Figure S1b), associated with the declining forage production (Verlinden et al., 2010). These results were also reported by Soares et al. (2001), who evaluated 16 cuts of *B. decumbens*, and even with biennial P replenishment (totalizing four biennia), pasture production peaked in the 2nd and 3rd biennium, followed by a gradual decline.

Few studies have been conducted in Brazil regarding the use of sewage sludge in pastures due to limitations imposed by current legislation until 2016, Resolution No. 375 (Brasil, 2006). However, the recent update, Resolution No. 498 (Brasil, 2020), authorized the use of this source in agriculture. This regulatory milestone fosters new perspectives for integrating sewage sludge into agriculture as alternative nutrient source, especially for the recovery of degraded pastures, with the aim of reducing environmental pressure and promoting circular economy in the country. However, further research is still needed to validate its agronomic efficiency in commercial crops, as the use of waste in agriculture will only be viable when it promotes equivalent or better responses than conventional fertilizers.

Total P accumulated in biomass

High initial accumulation of P in biomass (Figure 2a) followed by a decrease can be attributed to two factors: 1) initially, P absorption accompanies SDM yield, which is stimulated by cuts, however, as plants age, there is an increase in P use efficiency, leading to lower demand for the nutrient (Santos et al., 2002); 2) the removal of P by crops reduces its availability in the soil, limiting absorption by plants when the nutrient is not replenished (Soares et al., 2001).

The pelletization of MAP with SSC resulted in better P uptake by plants than MAP. The possible reasons for this are: 1) the gradual release of S+MAP can provide P to the soil solution during the first cycle of *Urochloa*. In contrast, MAP rapidly releases P in the first days after fertilization (Espinoza et al., 2023). This occurs at a stage when the root system is incipient, favoring rapid P immobilization in the soil and also reducing the residual effect of fertilization, as evidenced by the higher shoot P content content with S+MAP in the 1st, 4th, and 5th cycles. Additionally, the humic substances present in SSC can stimulate nutrient uptake by the rooting system (Monda et al., 2017; Waqas et al., 2018).

Similar results were found by Rodrigues et al. (2021) in soybean, in which there was a higher P accumulation in the treatment with OMFs based on sewage sludge compared to the mineral source. Few studies have evaluated P uptake by plants with organomineral fertilization, and even fewer in the literature consider sewage sludge as the organic matrix of OMF. However, the existing results are controversial, as while some studies show a higher P accumulation by plants with the use of OMFs, others show no difference in the mineral source. This was observed with OMFs based on chicken litter in the experiments of Frazão et al. (2019) in corn, and by Mumbach et al. (2020) in corn, wheat, and beans; as well as a lower P uptake in corn (Sakurada et al., 2016; Hawrot-Paw et al., 2022). These variations may be associated with the materials that compose the OMFs, the crop, the soil, and the evaluated period.

In the 5th and 6th cycles, SSC and SCP promoted greater accumulation of P (Figure 2a), indicating a slow solubilization of P from these sources, and therefore, they are capable of providing P in the medium to long term in the soil. This occurs because turning P available in the soil solution requires the mineralization of Po into Pi, as well as mobilization of Pi, which can be bound to metals such as Al, Ca, Mg, and in this case, primarily Fe, which is abundant in the compost used (Table S1). The levels of these elements vary depending on the treatment and origin of the sludge (O'Connor et al., 2013; Lemming et al., 2017).

Accumulation of P in the aboveground biomass was lower with S+ASD compared to its individual components (ASD and SSC) and other fertilizers due to the low solubility of the two raw materials. Additionally, pelletization may have further aggravated the restriction on P release into the soil solution for several reasons: 1) limitation in the dissolution of ions and diffusing molecules that facilitate pellet disintegration (Hettiarachchi et al., 2019); 2) pelletization of materials with different particle sizes may have resulted in a product more resistant to disintegration, as the finer particles settle into the voids, making the material more compact (Hettiarachchi et al., 2019); and 3) pellets reduce the specific surface area, which reduces the reactivity of the material (Brännvall et al., 2015). For these reasons, we recommend a more detailed physical characterization of fertilizers, including water disintegration testing.

The PAE showed that SSC, SCP, ASD, and S+ASD solubilized P more slowly, thus presenting potential for providing P in the medium to long term for crops. Meanwhile, the OMF may provide P at the beginning of cultivation and also has a greater residual effect than the conventional MAP fertilizer. This confers an advantage over other sources when considering use in crops that absorb larger amounts of P at the beginning of development. The differences found in the utilization of P by plants are due to the solubilization dynamics of each fertilizer. The efficiency of P use from slow-release sources such as ashes and organic compounds is generally lower than that of mineral sources when evaluated in short-term experiments. However, in prolonged cultivation, these sources can equal or even surpass the efficiency of fertilization with soluble mineral fertilizers (Lemming et al., 2017), as evidenced in our study. Additionally, the immediate release of a large quantity of soluble P may not confer an advantage over the gradual release, as this does not always translate into greater production gains (Talboys et al., 2016).

Soil P lability

Here, we present one of the first studies combining P fractionation and successive cropping to assess P-OMFs. We demonstrated that the slow release of P from OMFs may be associated with a reduction in organic P fractions (Figure 3), especially the less labile ones, which likely buffered the labile fractions. However, there is no evidence of direct Po uptake by plants (Lambers, 2022), thus plant associations with soil microbiota are necessary to mineralize Po fractions. This mechanism has already been proven for *Urochloa* species (Almeida et al., 2020), which increase root exudation to recruit microbiota capable of solubilizing, immobilizing, and mineralizing P (Hallama et al., 2019), particularly under low P availability in the soil (Almeida et al., 2020). Our results showed buffering of the labile fraction by Po, supporting the above mechanism, as labile Po is known to be a rapidly cycling reservoir (Sulieman and Mühling, 2021).

Successive cropping was essential in demonstrating the effects of controlled release of OMFs on soil P dynamics. For instance, the organomineral sources S+MAP and S+ASD showed an increase in labile P from the 4th to the 8th cycle, while the opposite occurred for the mineral raw materials MAP and ASD. These responses suggest that the mixture of ASD or MAP with SSC resulted in slower-release P sources (Figures 2 and 3), reinforced by the fact that even with P export by plants, there was replenishment of available P. These findings were also reported by Bogdan et al. (2023), who observed gradual release of P from OMFs for up to seven months with ryegrass cultivation, with an increase of up to 42 % in available P compared to a mineral source. This occurs because mineral nutrients are protected by bonds and adsorption mechanisms with the organic matrix in OMFs, giving organominerals greater efficiency than mineral fertilizers that rapidly release nutrients into the soil, favoring environmental losses (Kominko et al., 2017).

The null responses in the change of the non-labile Pi fraction (operationally defined as the most stable soil fraction) occur due to the “aging” of P in the soil, as the bonding energy between the element and soil minerals tends to increase with the contact time (Barrow et al., 2022). This interaction makes P desorption less reversible, making it difficult to recover adsorbed P in the soil matrix (Guedes et al., 2016; Barrow et al., 2023).

Our results demonstrate that non-labile P is more related to soil characteristics than P doses and sources. This argument is reinforced by the study of Raniro et al. (2022), who applied ASD, struvite, and triple superphosphate to sugarcane in soil similar to this study and found more P in the non-labile fraction. Frazão et al. (2019) also found a similar response when evaluating poultry litter-based organic fertilizers in Oxisol; however, slight alterations were observed in an Entisol. This effect is well known in soils with high P fixation capacity, as P is mainly found in non-labile forms due to the predominance of minerals such as hematite, gibbsite, and kaolinite, which form specific bonds with P, thus reducing its bioavailability (Lopes and Guilherme, 2016). Although recycled fertilizers from sewage sludge are slow-release P sources and induce a greater residual effect compared to soluble mineral fertilizers, it is necessary to understand how much of the released P in the soil will be truly bioavailable and for how long. Even though the less labile fractions may contribute to P replenishment in the solution, the speed at which this replenishment occurs may not be compatible with the plant’s demand.

CONCLUSIONS

Blended composted sewage sludge with soluble phosphate fertilizer (MAP) resulted in an organomineral fertilizer (S+MAP) more efficient in supplying P, promoting better biomass production of *Urochloa* than MAP. The S+MAP provides gradual release of P in the soil, ensuring higher initial growth and residual fertilization effect, capable of meeting P demands in crop establishment and signaling its potential as an alternative to soluble phosphate fertilizers, even in short-cycle crops.

On the other hand, the mixture of SSC (sewage sludge organic compost) with a less soluble P source (ASD - AshDec® pelletized) resulted in a product (S+ASD) that hindered P availability to plants and limited forage production, especially during establishment, being not recommended for short-cycle plants. Meanwhile, SSC and its pelletized form proved to be slow-release P sources, capable of providing P over a medium to long-term period, recommended for perennial crops with longer cycles, but also promoting similar production and P accumulation in biomass as MAP, indicating they can also be used in early stages of this crop.

Pelletized organomineral fertilizers can provide labile P to the soil for a longer period compared to soluble mineral fertilizers, thus having a greater residual effect and also contributing to increased P use efficiency, which is advantageous especially in highly weathered soils with high P fixation capacity as are the Brazilian soils.

SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://www.rbcsjournal.org/wp-content/uploads/articles_xml/1806-9657-rbcs-49-e0240124/1806-9657-rbcs-49-e0240124-suppl01.pdf

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SUPPLEMENTARY DATA

Table S1. Chemical analysis of sewage sludge and organic compost from the Bela Vista Wastewater Treatment Plant - Piracicaba, SP.

Determinações	Sewage Sludge		Organic compost	
	Dry basis (65°C)	Wet basis	Dry basis (65°C)	Wet basis
pH ($CaCl_2$ 0.01 M)	-	7.1	-	6.4
		------- % -------		
Total organic matter	72.64	11.47	67.92	65.42
Organic carbon	31.22	4.93	36.52	35.18
Total Mineral residual	20.96	3.31	26.76	25.78
Nitrogen (N)	6.78	1.07	3.73	3.59
Phosphorus (P_2O_5)	2.41	0.38	2.46	2.37
Potassium K_2O)	0.19	0.03	1.10	1.06
Calcium(Ca)	0.82	0.13	3.08	2.97
Magnesium (Mg)	0.32	0.05	0.63	0.61
Sulfur (S)	0.13	0.02	0.52	0.50
		------- mg kg^{-1} -------		
Cuper (Cu)	108	17	94	91
Manganese (Mn)	196	31	274	264
Zinc (Zn)	469	74	407	392
Iron (Fe)	12.483	1.971	13.073	12.592
Boron (B)	25	4	15	14
Sodium (Na)	969	153	898	865

Table S2. Soil pH and nutrient availability in the soil after 4th and 8th cycles under phosphate sources.

Source P	4th Cycle				8th Cycle			
	pH	K	Ca	Mg	pH	K	Ca	Mg
	-	--------- $mmol_c\ dm^{-3}$ ---------			-	--------- $mmol_c\ dm^{-3}$ ---------		
Control	4.7	4.7 a	19.0	6.4 a	4.9	9.8 a	18.5	9.4 a
MAP	5.2	0.5 b	21.0	2.3 b	5.1	1.6 b	14.9	3.1 b
SSC	5.2	0.4 b	26.1	3.3 b	4.8	0.6 b	18.9	4.2 b
SCP	4.7	0.4 b	19.9	2.5 b	4.6	0.6 b	15.8	2.1 c
ASD	5.2	0.4 b	22.6	2.2 b	5.0	0.6 b	19.0	4.3 b
S+ASD	5.2	0.4 b	23.5	2.9 b	4.9	1.3 b	20.0	4.0 b
S+MAP	4.9	0.4 b	20.6	1.7 b	4.4	0.4 b	12.4	1.4 c
Mean	5.0	1.0 b	21.8	3.0 b	4.8	2.1 b	17.1	4.1

Extraction methods: pH was measured in 0.01 mol L^{-1} $CaCl_2$; K extraction was performed with ion-exchange resin and determined using atomic emission spectrophotometry; Ca and Mg were extracted with KCl and determined using atomic absorption spectrophotometry. SSC = sewage sludge compost; SCP = sewage sludge compost pelletized; S+MAP = organic compost + MAP; S+ASD = organic compost + AshDec®; ASD = AshDec®; MAP = monoammonium phosphate.

Table S3. Soil P fractions by each extractor from the soil sampled after 4th and 8th cycles under phosphate sources.

Tratamento	- - - - Labile - - - -			- - - - -- Mod-labile - - - - -			- -- - - - - Non-labile - - - - - -			P total
	Pi-RTA	Pi--Bic	Po-Bic	Pi-Hid 0,1	Po-Hid 0,1	Pi-H-Cl	Pi-Hid 0,5	Po-Hid 0,5	Pi-re-sid	
- - - - - - - - - - - - - - - - mg kg-1 - - - - - - - - - - - - - - - -										
4th cycle										
Control	1.1	2.7	14.0	21.6	34.8	2.5	14.7	24.0	58.1	173.6
MAP	4.6	5.7	16.1	30.9	32.9	2.9	15.4	21.5	56.1	186.0
SSC	6.5	7.7	14.3	33.2	27.4	4.8	14.4	26.9	59.7	194.8
SCP	3.3	5.3	16.7	24.8	32.0	4.1	15.7	20.4	52.0	174.3
ASD	1.8	3.2	16.9	20.6	31.4	2.7	14.4	18.7	58.1	167.9
S+ASD	2.3	2.5	17.3	19.8	33.4	2.9	14.6	24.3	56.3	173.5
S+MAP	4.5	6.2	14.3	24.6	32.0	3.3	17.4	13.9	52.6	168.9
8th cycle										
Control	0.9	1.8	18.3	16.9	44.2	2.3	18.0	15.4	55.7	173.5
MAP	2.3	3.4	16.9	18.3	30.9	4.2	20.9	14.9	45.0	156.8
SSC	0.6	3.0	17.3	22.0	36.9	4.9	22.7	4.8	49.6	161.7
SCP	0.9	2.2	21.2	17.7	35.8	3.0	20.3	11.8	48.2	161.2
ASD	1.0	1.6	18.6	16.1	35.4	2.6	24.2	8.1	48.3	155.9
S+ASD	0.5	3.2	22.4	18.9	31.8	3.3	22.6	4.4	51.5	158.6
S+MAP	0.8	1.7	26.6	17.8	36.0	3.1	23.4	3.1	44.2	156.7

SSC = sewage sludge compost; SCP = sewage sludge compost pelletized; S+MAP = organic compost + MAP; S+ASD = organic compost + AshDec®; ASD = AshDec®; MAP = monoammonium phosphate.

Table S4. P-values of changes between the 4th and 8th cycle in soil P lability.

SourceP	Controle:	MAP:	SSC:	SCP:	ASD:	S+ASD:	S+MAP:
Pi labile	**0.035**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**0.027**	**<0.0001**
Po labile	**0.029**	0.670	**0.022**	**0.365**	**0.113**	**0.011**	**<0.0001**
Total labile	**0.118**	**0.067**	0.633	0.713	**0.001**	**0.056**	**0.052**
Pi mod-labile	**0.012**	**<0.0001**	**0.000**	**0.017**	**<0.0001**	0.777	**0.001**
Po mod-labile	**0.004**	0.525	**0.222**	**0.200**	**0.003**	0.615	**0.195**
Total mod-labile	**0.167**	**0.000**	**0.166**	0.816	0.620	0.508	**0.336**
Pi non-labile	0.841	**0.202**	0.854	0.988	0.662	**0.463**	0.586
Po non-labile	**0.0001**	**0.005**	**0.000**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Total non-labile	0.978	**0.000**	**0.069**	**0.095**	**<0.0001**	**0.040**	**0.090**

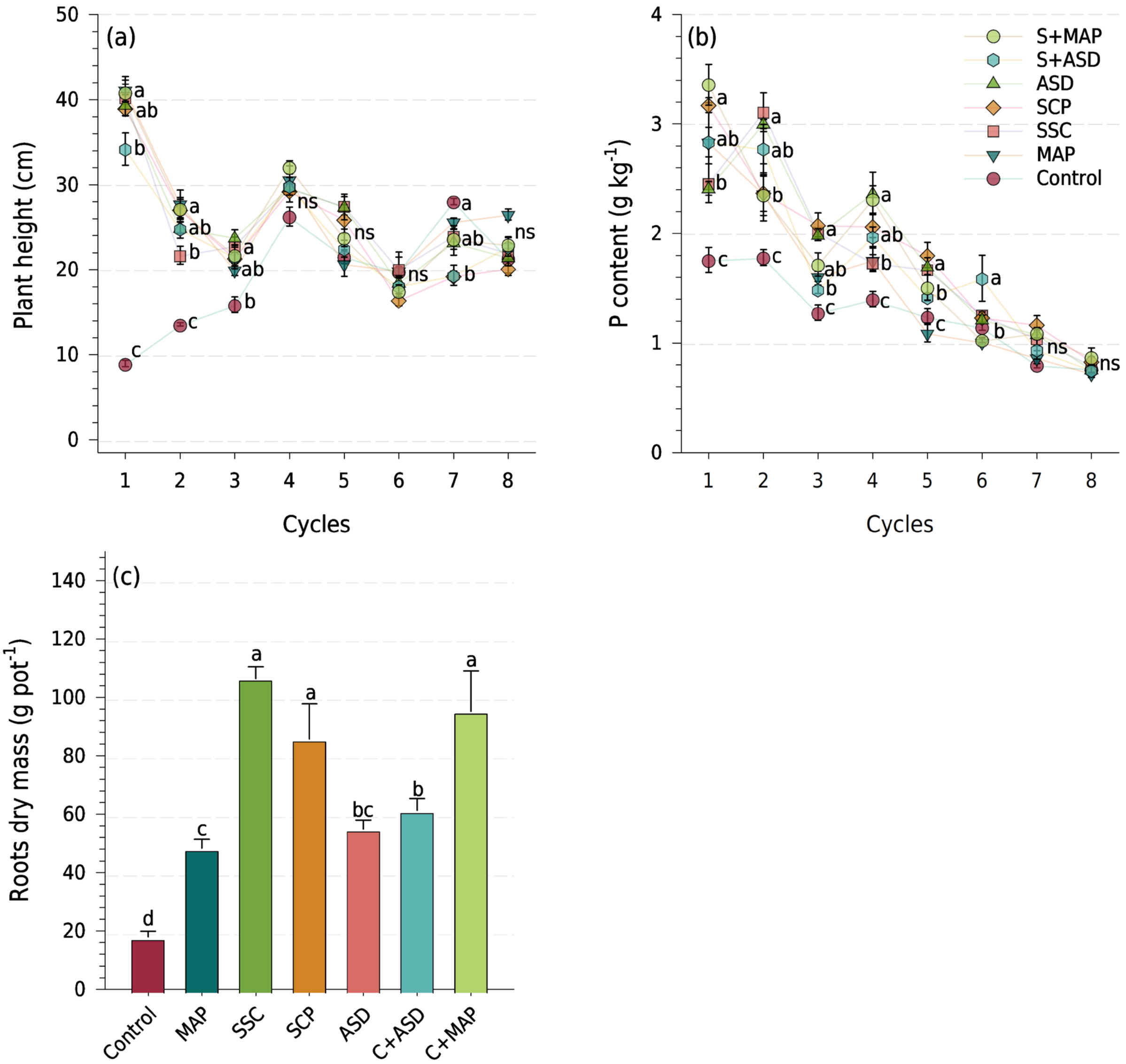

Figure S1. Plant height (A), leaf P content (B), and root dry mass (C) of *Urochloa* cultivated under phosphate sources. SSC = sewage sludge compost; SCP = sewage sludge compost pelletized; S+MAP = organic compost + MAP; S+ASD = organic compost + Ash-Dec®; ASD = AshDec®; MAP = monoammonium phosphate.

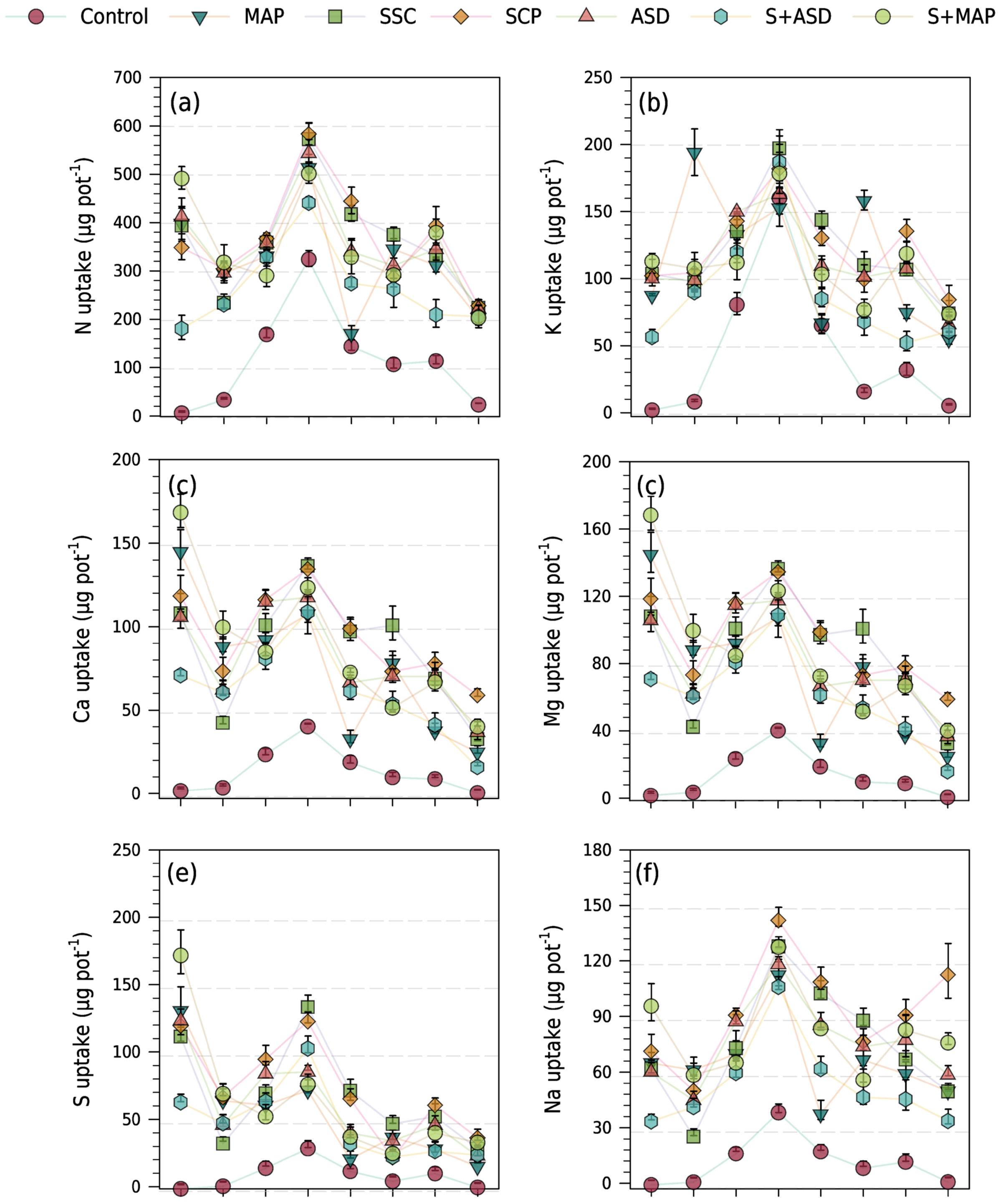

Figure S2. Element accumulation in aboveground biomass of *Urochloa* cultivated under phosphate sources. SSC = sewage sludge compost; SCP = sewage sludge compost pelletized; S+MAP = organic compost + MAP; S+ASD = organic compost + AshDec®; ASD = AshDec®; MAP = monoammonium phosphate.

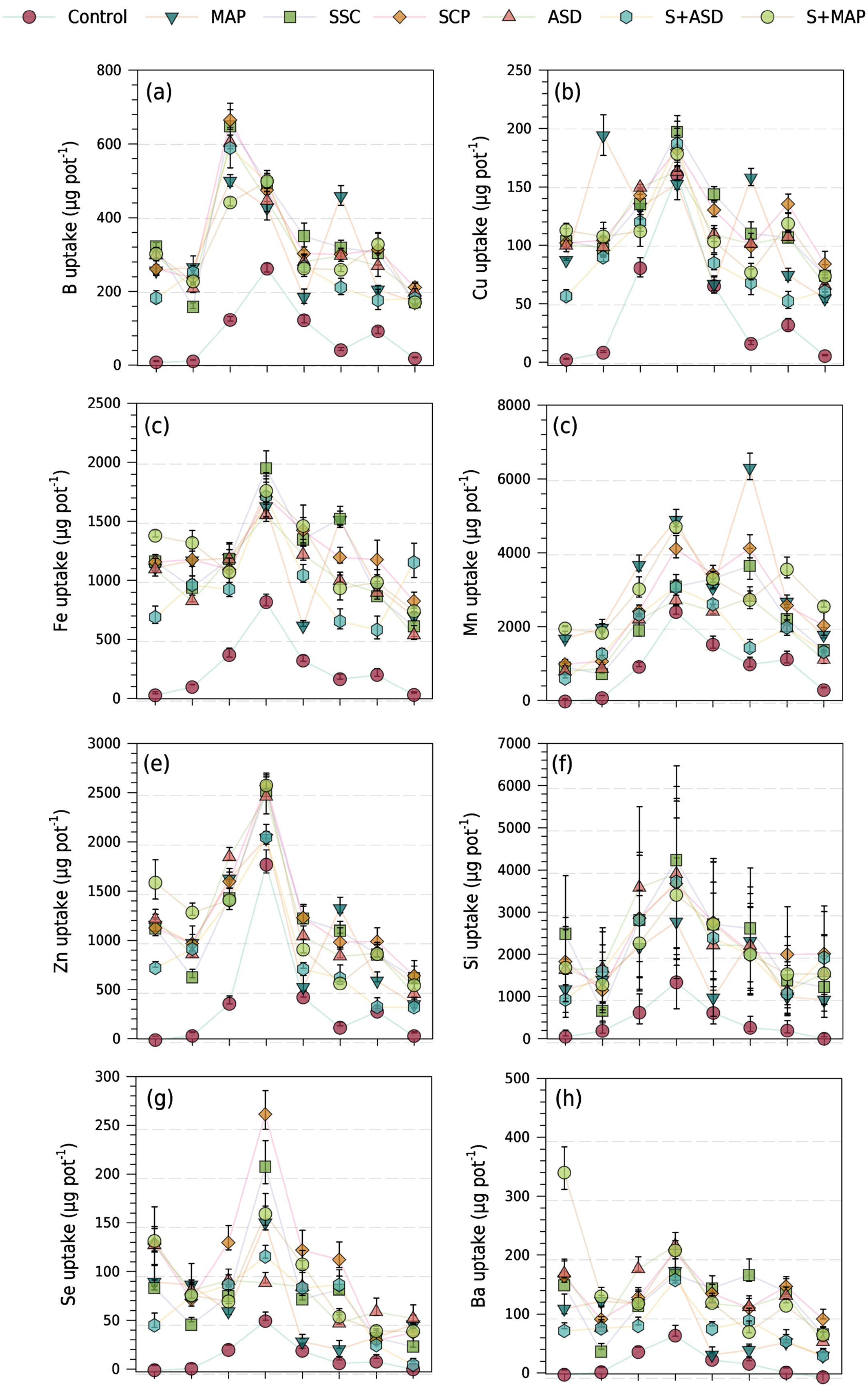

Figure S3. Accumulation of trace elements in aboveground biomass of *Urochloa* cultivated under phosphate sources. SSC = sewage sludge compost; SCP = sewage sludge compost pelletized; S+MAP = organic compost + MAP; S+ASD = organic compost + Ash-Dec®; ASD = AshDec®; MAP = monoammonium phosphate.