

Article

A Poultry Litter-Derived Organomineral Phosphate Fertilizer Has Higher Agronomic Effectiveness Than Conventional Phosphate Fertilizer Applied to Field-Grown Maize and Soybean

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Abstract: Inadequate disposal of poultry litter (PL) may promote eutrophication of water bodies due to its high nutrient content, including phosphorus (P). Thus, recycling P from PL to produce organomineral fertilizer (OMF), reduces the dependence on finite mineral P reserves, and also reduces P losses from soil. In this context, a field experiment was carried out to assess the agronomic effectiveness of a granular PL-derived OMF applied to maize and soybean in a highly weathered tropical soil. OMF was compared to single superphosphate (SSP) at five P rates between 0 and 70 kg ha⁻¹. The shoot dry weight (SDW) and grain yields of soybean and maize were affected by P rates; however, no difference between OMF and SSP was found. A similar trend was observed for soil P and P uptake. The leaf P content and soil pH were not affected by either P sources or P rates. Although there was no difference between OMF and SSP on the crop yields, OMF had the highest relative agronomic effectiveness based on the SDW. These results show that the production of granular OMF from PL is a viable alternative to conventional P fertilizers and reduces the dependence of mineral P reserves.

Keywords: *Zea mays*; *Glycine max*; single superphosphate; available phosphorus; recycling fertilizer; weathered soil; oxisol

1. Introduction

The world poultry meat production is approximately 100.6 million tonnes [1], which annually generates 76.5 million tonnes of poultry litter (PL). This organic manure has been used as source of nutrients such as nitrogen (N) and phosphorus (P) for crops but when inadequately disposed on the soil surface, it is often reported to cause serious environmental problems such as eutrophication of water bodies [2,3]. Recycling P from organic wastes such as PL is an important strategy to extend the useful life of world's mineral P reserves and at the same time to attenuate environmental contamination.

An alternative to recycling P from PL is the production of granular organomineral P fertilizer (OMF). PL-derived OMF has some advantages compared to the direct application of PL to crops. For instance, as PL does not contain a balanced amount of nutrients, complementary fertilizations are needed to supply the nutrient demand for crops, resulting in a higher cost associated with transportation and application compared to granular OMF.

The use of OMFs also improves soil organic matter content, soil microbial biomass, cation exchange capacity, complexation of metals, and improved nutrient release rates [4–6]. Furthermore, OMFs have been reported to prevent N losses from soil by leaching [7].

The slow-release property of OMFs [5,8,9] may also reduce P losses by adsorption reactions on the surface of the soil mineral. This property gives to OMF a great potential to improve P fertilization, especially in highly weathered tropical soils, which have, in general, a high P adsorption capacity and low fertilizer P recovery of conventional water-soluble P fertilizers [10]. However, Deeks et al. [11], and Morais and Gatiboni [12] observed no difference between OMFs and conventional mineral fertilizers in P availability in soil.

The response of crops to application of OMFs produced from different organic wastes has been evaluated [9,13–19]. For instance, Deeks et al. [11] compared conventional mineral fertilizer to a sludge-derived OMF applied to bean, oilseed rape, and cereals. These authors found no difference between P fertilizers on the crop yield over three cropping seasons. Similar results were found by Teixeira et al. [20] and Frazão et al. [9] in sugarcane and maize, respectively. However, Antille et al. [21] found that the average grain yields of four years with two OMFs was significantly lower than conventional mineral fertilizers. These contrasting results on the effectiveness of OMFs show the relevance of conducting new studies, especially at field scale, since factors such as soil management, fertilizer placement, and P losses affect the effectiveness of P fertilizers.

Thus, the objective of this field study was to assess the agronomic effectiveness of a granular organomineral P fertilizer produced from poultry litter applied to maize and soybean in a highly weathered tropical soil. We hypothesized that (i) response to OMF application varies with the crop and (ii) OMF has similar agronomic effectiveness to conventional mineral P fertilizers.

2. Materials and Methods

2.1. Production of Granular Organomineral Phosphate Fertilizer

The granular organomineral fertilizer (OMF) was performed in three steps, according to the method described in Frazão et al. [9]. First, both organic (poultry litter, PL) and mineral P sources (monoammonium phosphate, MAP) were oven dried at 60 °C until constant mass and ground separately in an industrial mixer and sieved (60 mesh). Based on the total P (Pt) content of each P source, the organomineral mixture (PL plus MAP) was formulated to have 20% of P (87.29 g kg⁻¹) and then homogeneously mixed in an industrial mixer with bentonite (2%). The OMF granules were produced using a granulator with an atomized 2% sodium silicate solution spray addition and then oven dried at 60 °C until constant mass. The OMF granules were sized between 3 and 4 mm and chemically characterized (Table 1) according to the methodology described in BRASIL [22].

Table 1. Chemical composition of treatments.

Fertilizers Composition	OMF _m ¹	OMF _s ²	SSP ³
pH (0.01 M CaCl ₂)	5.9	5.9	2.7
Organic carbon (g kg ⁻¹)	245.3	233.4	0
C:N ratio	4.34	3.87	-
P _{total} (g kg ⁻¹)	104.44	90.78	81.92
P _{water} (g kg ⁻¹)	55.08	58.09	43.64
P _{NAC} (g kg ⁻¹) ⁴	82.05	86.63	78.56
N _{total} (g kg ⁻¹)	56.5	60.3	0
K ₂ O (g kg ⁻¹)	17.35	17.77	0
B (mg kg ⁻¹)	12	9	0
Cu (mg kg ⁻¹)	199	62	27
Mn (mg kg ⁻¹)	885	800	657
Zn (mg kg ⁻¹)	471	312	321
Na (g kg ⁻¹)	16.95	15.46	14.7
Fe (mg kg ⁻¹)	13.96	14.66	12.6

¹ organomineral fertilizer used in the experiment with maize; ² organomineral fertilizer used in the experiment with soybean; ³ single superphosphate; ⁴ P soluble in neutral ammonium citrate plus water.

2.2. Site Description

The experiment was carried out in Piracicaba, São Paulo State, Brazil (22°41'29" S, 47°38'35" W and 564 m). According to Köppen's classification [23], the climate is humid subtropical with dry winter and hot summer (Cwa). The monthly rainfall and maximum and minimum air temperatures during the experiment are shown in Figure 1. The soil was classified as a clayey Rhodic Hapludox [24] and was chemically and physically characterized (Table 2) according to the methodology proposed by van Raij et al. [25] and Bouyoucos [26], respectively. The selected soil has a high phosphate adsorption capacity (Table 2 and Figure S1), which is supported by the presence of strong P adsorbents (e.g., hematite, gibbsite, and kaolinite), as revealed by X-ray diffraction analysis (Figure S2).

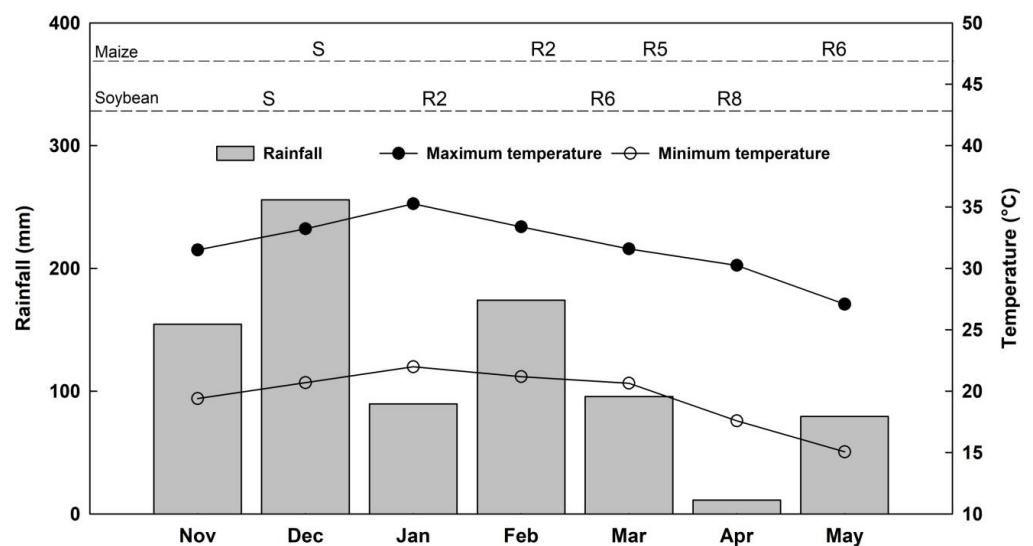


Figure 1. Average monthly precipitation and maximum and minimum air temperature during the experiment. The symbols at the top of the graph indicate the time of sowing (S) and the phenological growth stages of maize and soybean.

Table 2. Physicochemical properties of the soil used in this study.

pH	MPAC ¹	P	S	B	Cu	Fe	Mn	Zn	Ca	Mg	K	Al	CEC ₂	BS ³	OM ₄	Clay	Sand	Silt
5.0	1691.4	12	0.71	0.3	1.1	35	2.6	1.2	40	22	3.5	0	104	63	46	694	300	6

¹ maximum phosphate adsorption capacity; ² cation exchange capacity; ³ base saturation; ⁴ organic matter content.

2.3. Experimental Setup

To assess the agronomic effectiveness of OMF compared to conventional P fertilizer (single superphosphate, SSP), two simultaneous field experiments were carried out (maize and soybean). The experimental design was a randomized complete block with 2 × 4 + 1 factorial treatments and four replications. The factors corresponded to two P sources (OMF and SSP) and five P rates: 0, 17.5, 35, 52.5, and 70 kg P ha⁻¹ for maize and 0, 13, 26, 39, and 52 kg P ha⁻¹ for soybean.

Three months before the maize sowing, lime was applied to raise the soil base saturation to 70% [27] and incorporated with conventional tillage. Liming was not necessary for the soybean area since the soil base saturation (Table 2) was considered adequate for soybean [27]. Each plot consisted of eight 7 m long rows that were spaced at 0.8 m (maize) and 0.45 m (soybean). Treatments were manually deep-band applied (7 cm). Soybean (Monsoy 6410 IPRO[®]) and maize (hybrid Dekalb 395[®]) were sown at approximately 3 cm on the fertilizer row, maintaining 16 and 5 plants per linear meter, respectively.

Sowing mineral fertilization was performed according to the recommendations of van Raij et al. [27]. At thirty days after sowing (DAS), maize plants received 140 kg N ha⁻¹ as urea (topdressing). In order to apply equal amounts of N and K to the plots treated with OMF or SSP, we applied additional N and K (as KCl and urea) to the plot treated with SSP, based on the chemical composition of OMF (Table 1) and on the P rate.

2.4. Sampling and Chemical Analyses

Data samples were collected in four central rows, which were 1 m from the end of each plant row, at the R2 phenological growth stage of soybean [28] and maize [29] (50 and 65 DAS, respectively). Leaf samples for nutritional diagnosis were collected according to procedure described by Malavolta et al. [30]. Additionally, five plants of each plot were randomly collected, weighed, and then ground in a forage grinder. Subsamples of plant were oven-dried at 65 °C until constant mass and weighed for shoot dry weight (SDW) determination. Plant and leaf samples were ground (1 mm sieve) and digested in a mixture (2:1) of HNO₃ and HClO₄ [30]. Phosphorus concentration was determined by inductively coupled plasma optical emission spectrometry (ICP-OES iCAP 7000 series, Thermo Fisher Scientific Inc.).

Five soil subsamples were collected in the depth of 0–20 cm on the row fertilizer and thoroughly mixed to provide a composite sample and oven dried at 50 °C until constant mass and sieved (2 mm). Soil available P for plants extracted by anion exchange resin (P_{AER}) and soil pH (0.01 M CaCl₂) were determined according to van Raij et al. [25]. Originally, the P_{AER} is expressed in mg dm⁻³, but in this study, we converted the results to mg kg⁻¹, taking into account the soil density (dry weight basis).

2.5. Grain Yield Measurement and Calculations

The harvest of maize and soybean was performed at physiological maturity, corresponding to the R8 and R6 phenological stages of soybean and maize, respectively [28,29]. The grain yield was determined by manual harvesting of the plants contained in four 5 m long central rows per plot. Then, grains were weighed and the grain yield was calculated considering a moisture content of 130 g kg⁻¹.

P taken up by soybean and maize was calculated as the product of shoot dry weight (SDW) yield by the plant P concentration. Relative agronomic effectiveness (RAE) based on the P uptake, SDW, and grain yield were calculated according to Chien et al. [31] as follows: $RAE = (Y_{OMF} - Y_0) / (Y_{SSP} - Y_0) \times 100$, where Y_{OMF} is yield (grain or SDW) or P uptake in OMF treatment, Y_{SSP} is yield (grain or SDW) or P uptake in SSP treatment, and Y_0 is yield (grain or SDW) or P uptake in the control (no P added).

2.6. Statistical Analyses

A two-way analysis of variance (ANOVA) at the 0.05 level of error probability was performed using the PROC GLM procedure from the Statistical Analysis System—SAS v.9.3 (SAS Inc., Cary, NC, USA). When the F test was significant, the means of P sources were compared by using the least significant difference (LSD) and P rates effect adjusted to a linear or square root quadratic regression model. The square root quadratic model was chosen to assess the plant responses to P rates because it gives remarkably closer representations of the Mitscherlich's law of diminishing returns [32] compared to exponential and quadratic models [33]. Moreover, P sources means were contrasted with the control using Dunnett's test. The graphs and regression analysis were performed using SigmaPlot v.10.0 (Systat Software, San Jose, CA, USA).

3. Results

3.1. Plant Growth and Grain Yield

Shoot dry weight (SDW) and grain yields of field-grown soybean and maize increased significantly with increasing P rates; however, no difference between OMF and SSP was observed at all P rates (Figure 2). The SDW and grain yields of the control (no P addition)

were significantly lower than the P-amended plots. For maize, the SDW and grain yields were, on average, 23% and 8.0% higher in the P-amended plot relative to the control, respectively. With respect to soybean, P fertilization increased the SDW and grain yields by approximately 12% and 15.0%, respectively.

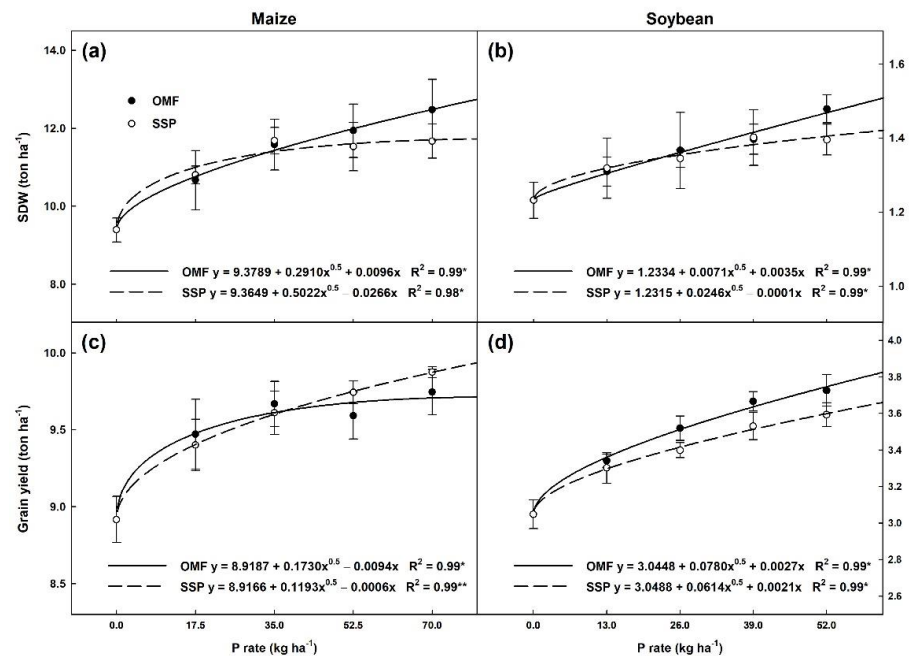


Figure 2. Shoot dry weight (SDW) and grain yields of maize (a,b) and soybean (c,d) as affected by rates of organomineral phosphate fertilizer (OMF) and single superphosphate (SSP). Error bars indicate standard error of mean ($n = 4$).

3.2. Fertilizer-Phosphorus Uptake and Nutritional Status

P uptake by both maize and soybean increased significantly with increasing P rates (Figure 3). For soybean, there was no difference between OMF and SSP, whereas, for maize, at the two highest P rates (52.5 and 70 kg P ha⁻¹), OMF was approximately 13.4% and 12.3% greater than SSP, respectively. P uptake by the control was significantly lower than P-amended crops.

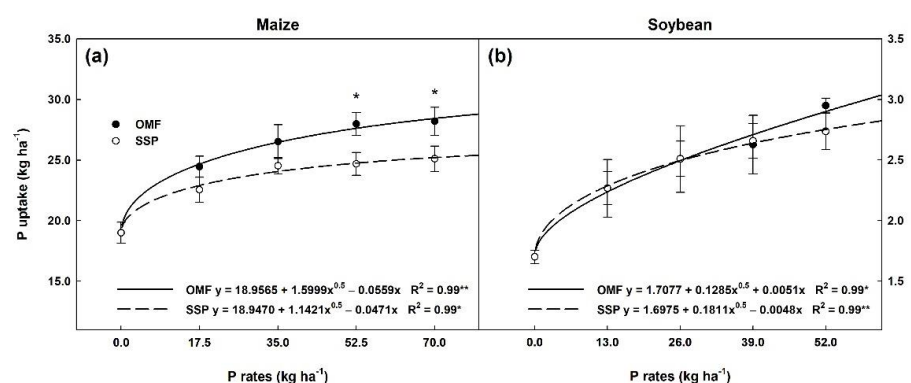


Figure 3. Phosphorus uptake by maize (a) and soybean (b) as affected by rates of organomineral phosphate fertilizer (OMF) and single superphosphate (SSP). Asterisk means differences between fertilizers within P rate (LSD's test, $\alpha = 0.05$). Error bars indicate standard error of mean ($n = 4$).

The P concentration in soybean leaves was affected by neither P sources nor P rates (Figure 4a,b). With respect to maize, there was an effect of P rates, although no regression

model was fitted to the data since the coefficient of determination was considered not satisfactory ($R^2 < 0.4$). Soybean and maize grown with no P-fertilizer addition (control) had similar leaf P content to P-fertilized plants.

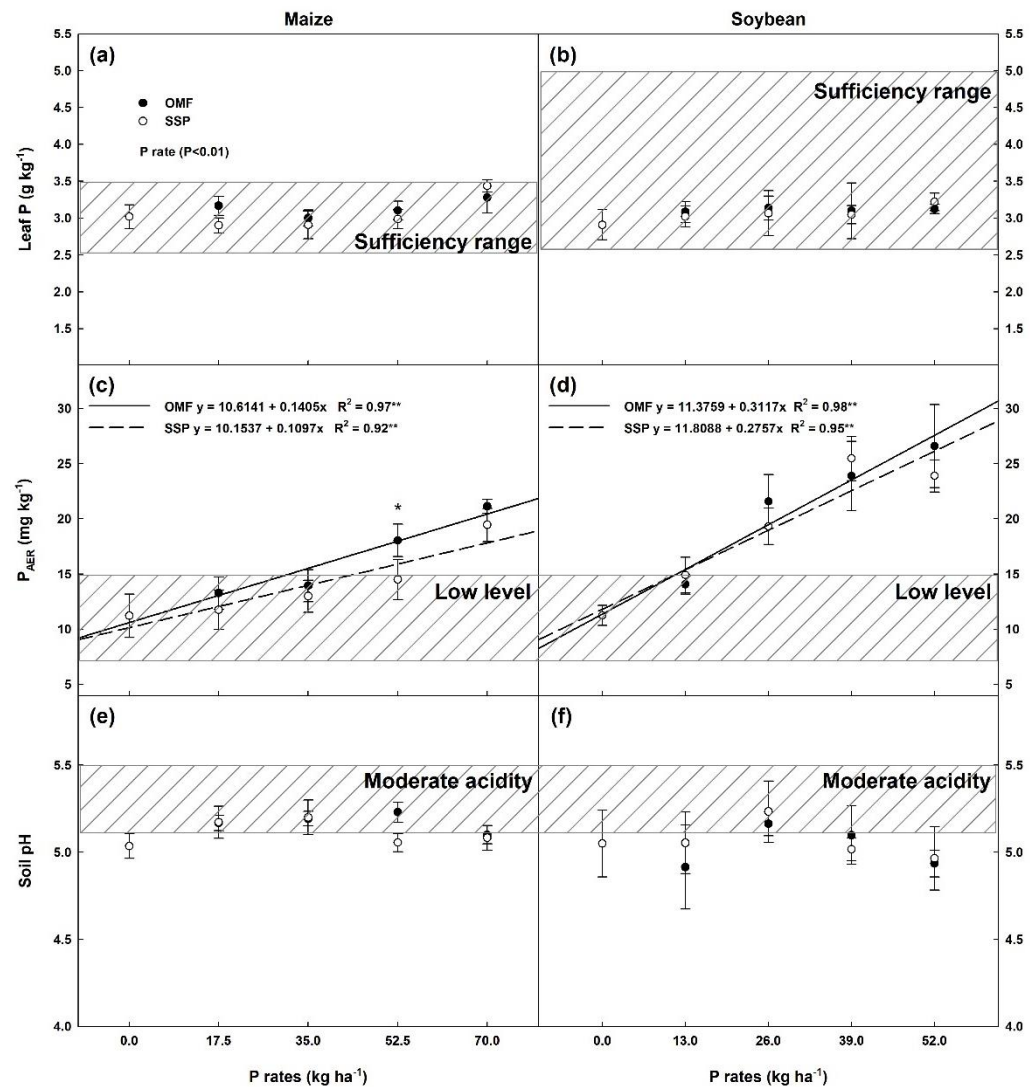


Figure 4. Phosphorus leaf phosphorus (P) content (a,b), soil available P extracted by anion-exchange resin (P_{AER}) (c,d) and soil pH (e,f) as affected by rates of organomineral P fertilizer (OMF) and single superphosphate (SSP). Plant P sufficiency range established by Malavolta et al. (1997) and soil available P and soil acidity evaluation described by van Raij et al. (1997). Asterisk means differences between fertilizers within P rate (LSD's test, $\alpha = 0.05$). Error bars indicate standard error of mean ($n = 4$).

3.3. Soil Test Phosphorus and Soil pH

Soil P extracted by anion-exchange resin (P_{AER}) increased linearly with P rates for both crops (Figure 4c,d). P_{AER} ranged from 11.26 to 21.14 mg kg⁻¹ (maize) and from 11.25 to 26.60 mg kg⁻¹ (soybean), which resulted in a higher slope in soil cultivated with soybean than maize. There was no difference between OMF and SSP at all P rates, except at 52.5 kg P ha⁻¹ (maize), where P_{AER} was higher with OMF. P_{AER} was significantly ($P < 0.01$) lower in the control treatment than P-fertilized plots for both crops. Soil pH was not affected by either P sources or P rates (Figure 4e,f). Soil pH ranged from 5.04 to 5.23 and from 4.92 to 5.23 in soil cultivated with maize and soybean, respectively.

3.4. Relative Agronomic Effectiveness

The results of relative agronomic effectiveness (RAE) based on the shoot dry weight yield (RAE-DW), grain yield (RAE-GY), and P uptake (RAE-P) are shown in the Table 3. All RAE indexes were affected by P sources and P rates applied to maize and soybean, except RAE-GY (maize) and RAE-P (soybean), which were not affected by P sources.

Table 3. Relative agronomic effectiveness (RAE) based on the shoot dry weight yield (RAE-SDW), P uptake (RAE-P), and grain yield (RAE-GY) of granular organomineral P fertilizer (OMF) compared to single superphosphate (SSP), in function of P rates applied to maize and soybean plants.

Crop	P Rate (kg ha ⁻¹)	RAE-SDW (%)		RAE-P (%)		RAE-GY (%)	
		SSP	OMF	SSP	OMF	SSP	OMF
Maize	17.5	100 a ¹	91.7 b	100 b	154.59 a	100 b	114.81 a
	35	100 a	96.65 b	100 b	137.15 a	100 b	108.48 a
	52.5	100 b	120.53 a	100 b	159.24 a	100 a	82.3 b
	70	100 b	136.54 a	100 b	151.62 a	100 a	86.67 b
	Mean	100 b	111.35 a	100 b	150.65 a	100	98.24
P source			* ²	*		ns ³	
P rate			*	*		*	
Source x rate			*	*		*	
Soybean	13	100 a	90.64 b	100 a	65.81 b	100 b	115.53 a
	26	100 b	120.33 a	100	100.9	100 b	134.53 a
	39	100	98.47	100	98.09	100 b	128.3 a
	52	100 b	151.94 a	100 b	121.78 a	100 b	124.69 a
	Mean	100 b	115.35 a	100	96.65	100 b	125.76 a
P source			*	ns		*	
P rate			*	*		*	
Source x rate			*	*		*	

¹ Different letter within row show difference between P source by LSD's test ($\alpha = 0.05$); ² significant at 0.05 error probability; ³ nonsignificant.

For maize, OMF promoted approximately 11.4% and 51% higher RAE-DW and RAE-P relative to SSP, respectively. Additionally, OMF had a similar RAE-GY as obtained with SSP. At lower P rates (17.5 and 35 kg P ha⁻¹), SSP promoted higher SDW yield, resulting in a higher RAE-DW than OMF; however, by increasing P rates, OMF is on average 23% greater than SSP.

With respect to soybean, OMF had a higher RAE-DW and RAE-GY relative to SSP (15% and 26% higher, respectively). No difference between OMF and SSP was observed for RAE-P, although the highest P rate had been 22% higher with OMF. OMF had a higher RAE-GY than SSP at all P rates, which gave OMF, on average, 26% higher RAE-GY. Similar results were observed for RAE-DW, except at the lowest P rate (13 kg P ha⁻¹), by which SSP was greater than OMF.

4. Discussion

4.1. Changes in Soil Phosphorus Availability

Soil phytoavailable P (P_{AER}) increased linearly with augmenting P rates applied to field-grown maize or soybean (Figure 4c,d). There was no difference between OMF and SSP at all P rates, excepted at 52.5 kg P ha⁻¹ for maize, by which OMF was greater than SSP. Soil P availability was considered low (7–15 mg kg⁻¹) or medium (16–40 mg kg⁻¹) for maize and soybean [27], depending on the P rate used. Morais and Gatiboni [12] also did not find a difference in soil-P availability between OMF and mineral P fertilizer in a clayey Nitisol. In contrast, Antille et al. [4] found significantly higher soil extractable P level with SSP compared to a biosolids-derived OMF at two P levels (150 and 300 kg ha⁻¹ of P₂O₅) and in two contrasting soils in terms of texture. Additionally, these authors found no difference between OMF and the control (no P addition) and attributed these results to the low water-solubility of OMF since most P is found as iron phosphate formed during the process of P removal from wastewater, which uses iron salts.

Although granular OMF produced from poultry litter has been reported to work as a slow-release P fertilizer [5], its use increased soil availability as with SSP. It most likely occurred

due the contrasting chemical composition of these P sources, where most P in OMF is found as $\text{NH}_4\text{-P}$ (MAP), whereas SSP is found as Ca-P. Since $\text{NH}_4\text{-P}$ has a much higher solubility in water compared to Ca-P, it might have contributed to increasing the P release rate from OMF, leading to similar P_{AER} values as found with SSP. Furthermore, the soil pH also contributed to these results since there was no effect of P sources (Figure 4e,f). Consequently, the speed and strength of P adsorption reactions on the surface of soil minerals were similar between OMF and SSP.

4.2. Crops Response to Phosphorus Fertilization

It is challenging to compare the agronomic effectiveness of granular organomineral P fertilizers (OMF) to conventional water-soluble P fertilizer (e.g., SSP, TSP, and MAP) since there are few publications in field scale. In this study, granular OMF not only promoted similar SDW and grain yields but also had a significantly higher relative agronomic effectiveness compared to a reference P fertilizer (SSP), applied to maize or soybean.

Field-grown maize and soybean amended with OMF taken up similar amount of P compared to SSP (Figure 3). However, OMF promoted higher P uptake by maize at the two highest P rates (52.5 and 70 kg P ha⁻¹). In contrast, Gurgel et al. [34] reported a significant lower SDW yield and lower P uptake by maize when fertilized with a OMF produced from sugarcane by-products compared to mineral fertilization at the recommend fertilizer dose. According to these authors, part of the nutrients in OMF was not available until 45 days after application, which may have contributed to these results. In our study, the use of MAP on production of OMF most likely increased the P release, leading to a similar P uptake pattern of SSP, as described before.

Although there was no difference in P uptake between OMF and SSP by both crops, the slope of the adjusted regression model of OMF was higher than SSP, which means that at higher P rates, a higher P uptake is expected when amended with OMF than SSP (Figure 3). We also observed a higher response of maize than soybean to increasing P rates, which might be related to the higher capacity of maize to explore a larger volume of soil since P has low mobility in soil [35].

By using the difference method [36], we estimated the fertilizer P recovery (%R) by the crops (data not shown). We found that only about 3% (2.2–4.3%) of the P applied was taken up by soybean. For maize, a higher %R was observed, which ranged from 11% to 26%. The %R by soybean and maize was on average 3.2% and 49.2% higher when fertilized with OMF relative to SSP, respectively. However, it is worth mentioning that the low %R values observed in this study are a result of the expressive amount of P taken up by the control (no P addition), which is deducted from P uptake of P-amended plants as calculated by the difference method. Thus, in soils with lower P availability for plants, the %R could be higher.

Sakurada et al. [5] compared an inorganic NPK fertilizer mix (3-15-2) with two OMFs (granular and pelletized) produced from poultry litter and mineral fertilizers (MAP and KCl), in four successive cropping cycles (maize). They found no difference between P sources on the SDW yield and total P uptake accumulated in four cropping cycles. The lowest accumulated %R was obtained with granular OMF (11.54%), followed by pelletized OMF (14.13%) and mineral fertilizer (15.6%). However, these values might be overestimated since they did not take into account the plant P derived from the soil (control treatment), as estimated by the difference method.

Maize and soybean plants amended with granular OMF produced a similar grain yield compared to SSP, as shown in Figure 2. A similar response was observed for SDW yield. In agreement with our results, Deeks et al. [11] observed no difference between conventional mineral fertilizer and a sludge-derived OMF on the yield of bean, oilseed rape, and cereals. Our results show a great potential of OMF substitute totally conventional mineral P fertilizers such as MAP, DAP, and TSP in a first cropping season.

It is known that maize and soybean are responsive crops to P fertilization in highly weathered soils, which have, in general, naturally low phytoavailable P [10]. In this study,

we also observed the response of soybean and maize to P fertilization (Figure 2). However, by comparing the SDW and grain yields obtained with the control treatment (no P applied) with P-amended crops, we found that the soil used did not significantly restrict the crop yield when compared to other studies, where higher responses were reported [37,38]. These results were not expected since the soil available P (P_{AER}) before the experiment was considered low for maize and soybean (Table 2), according to the recommendations of van Raij et al. [27]. Nevertheless, leaf P content (Figure 4a,b) in the control was within the sufficiency range [30], which indicates that there was a significant contribution from soil organic P for plant nutrition. This is supported by the adequate soil organic matter content (Table 2), taking into account its textural class [39].

Organic P forms such as phosphomonoesters and phosphodiesteres can be a source of P for crops through hydrolysis performed by phosphatases produced by plant roots and soil microorganisms [40]. Furthermore, non-phytoavailable P forms are also mobilized by organic anions such as citrate, oxalate, and malate released by plant roots [40]. Carvalhais et al. [41] reported a significant P mobilization by organic anion and carbohydrates released by maize roots under low P availability. Similar processes for soybean were described by Wang et al. [42]. Thus, these plant and microbial strategies to mobilize soil P forms show a possible condition where control plants could have obtained P from the soil.

Although there was no significant difference between P fertilizers on the SDW yield, the RAE-DW of OMF was 11.35% and 15.35% higher than that of the SSP for maize and soybean, respectively (Table 3). The RAE-DW of OMF increased significantly with P rates. Similarly, Antille et al. [43] found that two OMFs had a similar agronomic efficiency compared to mineral fertilizers based on the SDW yield of ryegrass (*Lolium perenne* L.) in two crop seasons. With respect to RAE based on the grain yield (RAE-GY), OMF had a similar and 25.8% higher RAE-GY than SSP in maize and soybean, respectively. Furthermore, the OMF had a RAE-P 50.7% greater than SSP in maize. The significant higher RAE-P is result of higher P uptake in soil amended with OMF, especially at the highest P rates (Figure 3). In soybean, as there was no effect of P sources on P uptake, similar RAE-P between OMF and SSP is expected.

5. Conclusions

Our results show that the production of OMF from organic wastes such as poultry litter (PL) could be a viable alternative to substitute mineral P fertilizers on growth and production of maize and soybean plants. PL-derived OMF not only gives similar crop yields but also has a higher agronomic effectiveness than that of conventional mineral P fertilizer (SSP). However, maize was more responsive to OMF application than soybean. Moreover, OMF may have even a greater potential to improve crop yield and P fertilization since OMF works as a slow-release P fertilizer. However, there is a need for long-term field experiments to assess the residual effect of OMFs as well as their potential to mitigate nutrients losses from soil and improve the P fertilization efficiency in highly weathered tropical soils.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/su132111635/s1>, Figure S1: Maximum phosphate adsorption capacity (MPAC) of a clayey Rhodic Hapludox as adjusted to the Langmuir isotherm, Figure S2: X-ray diffractograms of non-deferrified (A) and deferrified (B) clay fraction at room temperature (K-25 °C), K⁺ heated at 350 °C and 550 °C (K-350 °C and K-550 °C, respectively), Mg²⁺ at room temperature (Mg-25 °C) and Mg²⁺ solvated with ethylene glycol (Mg+EG). Gibbsite (Gb), Hematite (Hm), Kaolinite (Kt), Quartz (Qz) and Vermiculite (Vt).

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