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CENTER FOR NUCLEAR ENERGY IN AGRICULTURE

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Agronomic effectiveness of a poultry litter-derived organomineral phosphate fertilizer in maize and soybean

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To my parents
To my brother and sister
To my sweet goddaughter
I DEDICATE

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“*There is nothing more powerful than an idea whose time has come*.”
Victor Hugo

ABSTRACT

FRAZÃO, J. J. **Agronomic effectiveness of a poultry litter-derived organomineral phosphate fertilizer in maize and soybean**. 2017. 65 p. Tese (Doutorado) – Centro de Energia Nuclear na Agricultura, Universidade de São Paulo, Piracicaba, 2017.

Most soils in the world have low phosphate (P) availability, especially in tropical regions where most soils are highly weathered and rich in strong P adsorbents such as iron and aluminium sesquioxides, which limit the plant growth. Thus, large amounts of P fertilizers have been applied annually on crops to meet P requirements, which have declined the world's mineral P reserves.On the other hand, large amounts of P can be recycled from organic wastes like poultry litter (PL). However, inadequate disposal of PL on soil surface promotes environmental contamination (e.g., eutrophication). In this context, the use of PL to produce organomineral P fertilizers (OMF) represents a suitable alternative to recycle P from PL and reduce the dependence on mineral P reserves. In this study, we carried out a pot and a field experiment to evaluate the effectiveness of a granular PL-derived OMF in maize (*Zea mays* L.) and soybean (*Glycine max* L.).The pot experiment was conducted in a greenhouse arranged in a completely randomized design with 2x4+1 factorial treatments with four replications. We tested OMF against triple superphosphate (TSP) at 0, 25, 50, 75 and 100 mg P kg^{-1} in two contrasting soils in term of P adsorption capacity (PAC): a clayey Oxisol and a sandy Entisol. In the soil with high PAC (Oxisol), granular OMF was as effective as TSP, but in the Entisol, TSP promoted higher P uptake and higher fertilizer P recovery than OMF. Thus, the agronomic effectiveness of OMF is dependent on the P adsorption capacity of soil. With respect to the field trial, we used a randomized complete block with 2x4+1 factorial treatments and four replications. The soil is classified as Ultisol. The factors corresponded to two P sources (OMF and single superphosphate, 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. There was no difference between OMF and SSP on the shoot dry weight (SDW) and grain yields. Similar trend was observed for plant P uptake.Additionally, OMF had a significant higher relative agronomic effectiveness (RAE) based on the SDW compared to SSP. Furthermore, OMF also had a higher RAE based on the P uptake than SSP in maize and a higher RAE based on the grain yield in soybean. Thus, we conclude that OMF is an effective substitute to conventional P fertilizers and, at the same time contributes to reducingenvironmental contamination associated to inadequate disposal of PL.

Keywords: *Zea mays* L. *Glycine max* L. Oxisol.Entisol. Phosphorus use efficiency.

RESUMO

FRAZÃO, J. J. **Eficiência agronômica de um fertilizante organomineral produzido a partir de cama de frango em milho e soja**. 2017. 65 p. Tese (Doutorado) – Centro de Energia Nuclear na Agricultura, Universidade de São Paulo, Piracicaba, 2017.

A maioria dos solos no mundo possui baixa disponibilidade de fósforo (P), especialmente nas regiões tropicais, onde a maioria dos solos são bastante intemperizados e ricos em fortes adsorventes de P como sesquióxidos de ferro e de alumínio, os quais limitam o crescimento das plantas. Assim, grandes quantidades de fertilizantes fosfatados têm sido aplicadas anualmente em cultivos para atender a demanda de P pelas culturas, o que tem reduzido as reservas minerais de fósforo. Por outro lado, grandes quantidades de P podem ser recicladas a partir de resíduos orgânicos como a cama de frango (CF). No entanto, aplicação inadequada de CF no solo resulta em contaminação ambiental (ex. eutrofização). Nesse contexto, o uso de CF na produção de fertilizantes organominerais (FOM) representa uma alternativa adequada para reciclar P de CF e ao mesmo tempo, reduzindo a dependência das reservas minerais de P. Nesse estudo, foram conduzidos dois experimentos, um em vasos e outro em condições de campo com intuito de avaliar a eficiência de um fertilizante organomineral granulado produzido a partir de CF nas culturas do milho (*Zeamays* L.) e da soja (*Glycinemax* L.). O primeiro foi conduzido em casa de vegetação utilizando o delineamento inteiramente casualizado em esquema fatorial 2x4+1 com quatro repetições. FOM foi comparado com superfosfato triplo (SFT) nas doses de 0, 25, 50, 75 e 100 mg P kg^{-1}em dois solos contrastantes em termos de capacidade de adsorção de P (CAP): um Latossolo argiloso e um Neossolo arenoso. No solo com elevada CAP (Latossolo), o FOM foi mais eficiente que o SFT, porém no Neossolo, SFT promoveu maior absorção de P bem como maior recuperação do P aplicado comparado ao FOM. Dessa forma, a eficiência agronômica do FOM granulado depende da CAP do solo. Em relação experimento de campo, foi utilizado o delineamento de blocos completos casualizados em esquema fatorial 2x4+1 com quatro repetições. O solo da área é classificado como Nitossolo. Os fatores correspondem a duas fontes de P (FOM e superfosfato simples, SFS) e cinco doses de P: 0, 17.5, 35, 52.5 e 70 kg P ha^{-1}para milho e, 0, 13, 26, 39 e 52 kg P ha^{-1}para soja. Não houve diferença entre FOM e SFS na produtividade de grãos, produção de massa seca de parte aérea de plantas (MSPA) e na absorção de P. Adicionalmente, FOM teve uma maior eficiência agronômica relativa (EAR) como base na produção de MSPA comparado ao SFS. Além disso, FOM também obteve maior EAR baseado na absorção de P na cultura do milho e maior EAR com base na produtividade de grãos na cultura da soja. Conclui-se que FOM pode substituir fertilizantes fosfatados convencionais bem como, reduzir a contaminação ambiental decorrente da disposição inadequada de CF.

Palavras-chave: *Zea mays* L. *Glycine max* L. Latossolo. Neossolo. Eficiência de uso de fósforo.

SUMMARY

1 INTRODUCTION

Phosphorus (P) availability in highly weathered tropical soils is naturally low since most soluble P is rapidly adsorbed by iron and aluminium hydrous oxides. Thus, continuous P fertilizer applications are important for the maintenance of crop yield in these soils, contributing for a reduction on the word's P mineral reserves.

Recycle P from organic wastes like poultry litter (PL) has been reported to be a suitable alternative source of P for crops since it not only reduces the dependence of mineral P reserves,but at the same time reduces environmental problems associated to the inadequate disposal of organic wastes. However, asthe production PL is not well distributed across agricultural areas, expensive cost of transportation and application to crops as well as the low nutrients content has contributed to the low adherence of farmers to use organic wastes in cropping system compared to mineral fertilizers.

In this context, the use of PL to produce organomineral P fertilizers (OMF) is an alternative to recycle P from PL and increase the utilization of organic P sources in agriculture. Thus, assess the response of crops to OMFs application is important to determine the agronomic effectiveness of OMFs compared to conventional P fertilizer. However, few scientific publications have evaluated the effectiveness of OMFs, especially at field scale.

Thus, we aimed with this research assess the agronomic effectiveness of a PL-derived OMF comparatively to conventional P fertilizers applied to maize and soybean in a highly weathered tropical soil in field scale. Furthermore, we also investigated the effect of soil mineralogy, plant and microbial processes affecting the effectiveness of OMFs and the P fractions in the soil. We hypothesized that PL-derived OMF is as effective as conventional P fertilizers and that soil type and crops affect the effectiveness of this OMF.

2 AGRONOMIC EFFECTIVENESS OF A GRANULAR ORGANOMINERAL PHOSPHATE FERTILIZER IS AFFECTED BY PHOSPHATE ADSORPTION CAPACITY OF SOIL: A ^{32}P-LABELLING STUDY

Abstract

We evaluated the agronomic effectiveness of a granular poultry litter-derived organomineral phosphate fertilizer (OMF) compared to triple superphosphate (TSP). Granular OMF was tested against TSP in two contrasting soils (Oxisol and Entisol) by using isotope dilution with ^{32}P. P rates used were 0, 25, 50, 75 and 100 mg kg^{-1}. We assessed the shoot and root dry yield of maize, plant P derived from fertilizer (Pdff), sequential soil P fractionation, phosphatases activity and microbial carbon (C_{mic}) in rhizospheric soil. Shoot and root dry yield increased in both soils by raising P rates from both P fertilizers. We found no difference in Pdff and fertilizer P recovery between OMF and TSP in the Oxisol, but in the Entisol, TSP was greater than OMF. Nevertheless, acid and alkaline phosphatases (Pases) activity and C_{mic} were affected by P rates and P sources in both soils. In the Oxisol, we observed higher Pases activities with TSP than OMF at the lowest P rates (25 and 50 mg kg^{-1}), whereas in the Entisol, higher means were observed in soil amended with OMF. C_{mic} was higher in the Oxisol than in the Entisol and, OMF promoted higher C_{mic} than TSP, in the Entisol. In the Oxisol, there was no difference between OMF and TSP in all P pools, but higher readily phytoavailable P and lower moderately labile P fractions were obtained with OMF. In the Entisol, the labile P pool was greater with TSP. In highly weathered soils, granular OMF represents a promising alternative to conventional P fertilizers, and soil P fractions are controlled by soil P adsorption capacity.

Keywords: *Zea mays* L., isotopic dilution, Oxisol, Entisol, poultry litter, soil phosphorus fractions.

2.1 Introduction

Phosphorus (P) is an essential element for plant growth and its deficiency in weathered tropical soils is often reported. Such soils have high content of strong P adsorbing minerals such as hematite, goethite and gibbsite (ATKINSON; PARFITT; SMART, 1974; MULJADI; POSNER; QUIRK, 1966; PARFITT; ATKINSON; SMART, 1975), which results in low fertilizer P recovery by crops. Thus, frequent P fertilization is required for the maintenance of crop yields, which reduces finite non-renewable resources of P. In thiscontext, the use of organic manures like poultry litter (PL) is an alternative to reduce the dependence on mineral P resources.

According to the United States Department of Agriculture, in 2016 the world poultry production was approximately 89.55 million metric tons (USDA, 2017). Considering that to produce 1 ton of poultry, 0.76 ton of PL (on dry basis) is generated (MIGLIAVACCA; YANAGIHARA, 2017), about 68.06 million tons of PL is produced annually. Furthermore, PL contains on average 1.77% P (ROGERI et al., 2016; YADVINDER-SINGH et al., 2009), representing a large P pool which can be recycled and used in cropping systems. However, inadequate disposal of PL on soil surface is often reported to cause serious environmental problems like eutrophication of water bodies (CORRELL, 1998; SCHROEDER; RADCLIFFE; CABRERA, 2004; SHARPLEY, 1997). Thus, strategies to increase the utilization of PL associated with reduction of environmental risks are fundamental. In this context, the use of PL for production of granular organomineral P fertilizers (OMF) is a promising option, from both environmental and economic aspects.

The association of mineral P sources with PL in OMF reduces the P adsorption by soil minerals since organic compounds interact positively with P (GUPPY et al., 2005), consequently improving the efficiency of inorganic P fertilizers. Although several authors have evaluated the response of many crops to application of OMF produced from different organic wastes (ANTILLE et al., 2017; CORRÊA et al., 2016; KOMINKO; GORAZDA; WZOREK, 2017; MAZEIKA; STAUGAITIS; BALTRUSAITIS, 2016; OLIVÉRIO et al., 2011; RAO et al., 2007), the potential for improvement of P fertilization has been poorly studied. Gondek and Filipek-Mazur (2005) observed higher plant P content in maize and sunflower fertilized with OMF compared to mineral fertilization. However, in a more recent study, Sakurada et al. (2016) found that granular OMF did not increase either the shoot dry matter yield or the P recovery by maize in two consecutives cropping cycles in a clayey Oxisol.

Although soil P adsorption capacity can affect the efficiency of OMF, no study in this respect has been performed. In this work, we hypothesized that OMF is more efficient than a water soluble P fertilizer (triple superphosphate) in a high P adsorbing soil (Oxisol) and a lower efficiency in sandy soil (Entisol). To check these hypotheses, we carried a pot trial to assess the efficiency of a granular OMF in these two contrasting soils in terms of P adsorption capacity using the isotopic dilution method with ^{32}P.

2.2 Material and methods

2.2.1 Organomineral fertilizer production

The production of the granular organomineral fertilizer involved the following steps. First, both organic (poultry litter, PL) and mineral P sources (triple superphosphate, TSP) were oven dried at 60 °C until constant weight 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 TSP) was formulated to have 20% P, and then was homogenously mixed in an industrial mixer with bentonite (2%). The OMF granules was produced using granulator with addition of a 2% sodium silicate solution spray and then oven dried at 60 °C until constant weight. The OMF granules were sized between 3 and 4 mm and chemically characterized (Table 2.1) according to the method described in Brasil (2014).

Table 2.1 –Chemical composition of the fertilizers

Property	OMF	TSP
pH (0.01 M $CaCl_2$)	4.3	3.05
Organic carbon (%)	20.75	0
C:N ratio	9.69	-
P_{total} (%)	9.57	20.73
P_{water} (%)	4.77	17.27
P_{NAC} (%)	9.25	20.47
P_{CA} (%)	8.24	18.14
N_{total} (%)	2.14	0
K_2O (%)	2.44	0
B (mg kg^{-1})	15.3	0
Cu (mg kg^{-1})	360	59.5
Mn (mg kg^{-1})	506	595
Zn (mg kg^{-1})	442	382
Na (g kg^{-1})	14.13	0
Fe (g kg^{-1})	10.78	15.78

OMF, organomineral phosphate fertilizer.TSP, triple superphosphate.P_{NAC}, P soluble in neutral ammonium citrate plus water.P_{AC}, P soluble in 2% citric acid.

2.2.2 Experimental setup

The experimental design was completely randomized with 2x4+1 factorial treatments and four replications. The factors corresponded to two P sources: i) granular organomineral fertilizer (OMF) and ii) triple superphosphate (TSP), and five P rates: 0, 25, 50, 75 and 100 mg kg^{-1} soil. We selected two contrasting soils in terms of P adsorption capacity (Table 2.2): an Oxisol (Typic Hapludox) and an Entisol (Typic Quartzipsamment) (SOIL SURVEY STAFF, 2014).

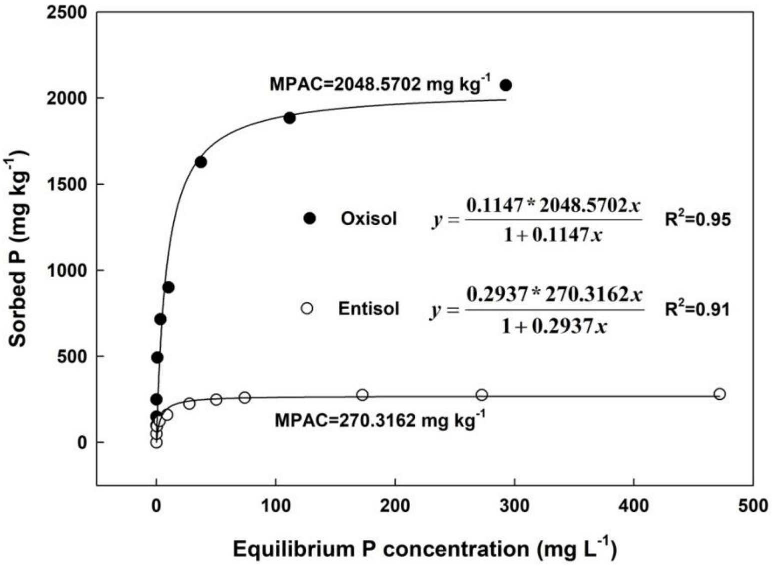
Samples from each soil were used for chemical (VAN RAIJ et al., 2001), particle-size (BOUYOUCOS, 1926) and mineralogical (X-ray diffraction, XRD) analyses. The maximum P adsorption capacity (MPAC) was determined by shaking 2.5 g of soil at 147 g for 36 h in 25 mL of 0.01M $CaCl_2.2H_2O$ with increasing levels of P (added as KH_2PO_4) (0, 5, 10, 25, 50, 75, 100, 200, 300 and 500 mg L^{-1}). The MPAC was obtained after fitting the Langmuir isotherm (Figure 2.1). The MPAC values (mg kg^{-1}) of the Oxisol and the Entisol were 2048.87 and 270.32, respectively. The XRD diffractograms (Figure 2.2) showed the presence of strong P adsorbents (e.g., goethite, hematite, gibbsite) in the clay fraction of both soils. The significantly higher MPAC of the Oxisol (Table 2.2) is explained by its higher clay content, which contains iron and aluminium oxides, as revealed by XRD analysis.

Table 2.2 – Chemical and physical properties of the selected soils

Property	Oxisol	Entisol
pH (0.01 M $CaCl_2$)	4.5	4.3
Organic matter (g kg^{-1})	5	5
Resin P (mg kg^{-1})	2	6
Maximum P adsorption capacity (mg kg^{-1})	2048.6	270.3
Exchangeable Ca^{2+} ($mmol_c$ kg^{-1})	4	3
Exchangeable Mg^{2+} ($mmol_c$ kg^{-1})	1	1
Exchangeable K^+ ($mmol_c$ kg^{-1})	0.1	0.1
$H^+ + Al^{3+}$ ($mmol_c$ kg^{-1})	42	22
Zinc (mg kg^{-1})	0.2	0.3
Sulphate (mg kg^{-1})	30	7
Cation exchange capacity ($mmol_c$ kg^{-1})	47	26
Clay (g kg^{-1})	667	62
Silt (g kg^{-1})	123	8
Sand (g kg^{-1})	210	930

A pot trial was carried out in a greenhouse using sealed plastic bags filled with 5 kg of soil (dry weight) from the surface layer (0-20 cm). Soil acidity was corrected with $CaCO_3$ to achieve a base saturation of 70% (VAN RAIJ et al., 1997) by incubating the soil for 30 days at 70% water-holding capacity (WHC).

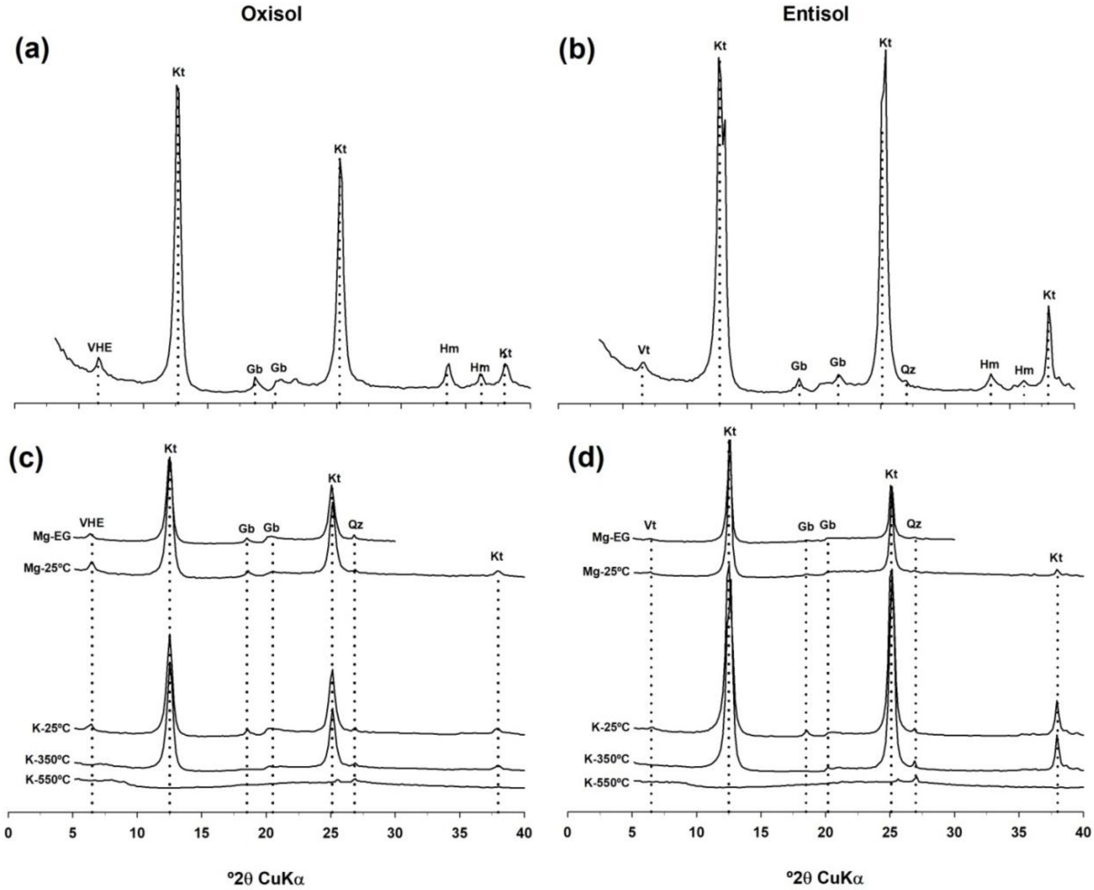
Figure 2.1 – Maximum phosphate adsorption capacity (MPAC) of the selected soils as adjusted to the Langmuir isotherm



To quantify accurately the P taken up by the plants from the fertilizers, the isotopic dilution method with ^{32}P (indirect method) was used. For this, soils were uniformly labelled with 1.76 MBq kg^{-1} of carrier-free ^{32}P-orthophosphate by incorporating 20 g of dry sand previously labelled with ^{32}P, and then the soil was thoroughly mixed and incubated for 10 days to allow isotopic equilibrium between ^{32}P and ^{31}P. The soil moisture was adjusted daily to 70% WHC.

The treatments were deep band applied (7 cm), in which five maize seeds (*Zea mays* L., cv. Pioneer P4285H) were sown at 1 cm in the fertilizer row. Plants were thinned to 2 plants per pot 5 days after sowing. Soil fertility was corrected by applying nutritive solution containing the following nutrients (mg kg^{-1} soil): N (150), K (150), Cu (2), Fe (5), Mn (1), Mo (1), Zn (5) and B (1.5). N and K doses were parcelled out at seven and 25 days after sowing (DAS) (70 and 80, respectively). The other nutrients were applied at seven DAS. In order to assess the isolated effect of P addition, we balanced the inputs of macro and micronutrients (through nutritive solution) between treatments considering their chemical composition (Table 2.1). The pots were irrigated daily, and moisture was maintained near 70% WHC by weighing.

Figure 2.2 –X-ray diffractograms of non-deferrified (a and b) and deferrified (c and d) clay fraction at room temperature (K-25°C), K^+ heated at 350°C and 550°C (K-350°C and K-550°C, respectively), Mg^{2+} at room temperature (Mg-25°C) and Mg^{2+} solvated with ethylene glycol (Mg+EG). Gibbsite (Gb), Hematite (Hm), Kaolinite (Kt), Quartz (Qz), Vermiculite (Vt) and Vermiculite with hydroxy-aluminium interlayer (VHE)



2.2.3 Chemical analyses

At 45 DAS, four soil subsamples were collected at depth of 0-10cm adjacent to the fertilizer row and thoroughly mixed to provide a composite sample, which was oven dried at 50 °C until constant weight and sieved (2 mm). Soil P fractions were assessed following the method proposed by Hedley, Stewart and Chauhan (1982) with later modifications by Condron, Goh and Newman (1985). P fractions were grouped into pools according to their lability (CROSS; SCHLESINGER, 1995): labile P (Pi_{AER}, Pi_{Bic} and Po_{Bic}), moderately labile P ($Pi_{NaOH-0.1}$, $Po_{NaOH-0.1}$ and Pi_{HCl}) and non-labile P ($Pi_{NaOH-0.5}$, $Po_{NaOH-0.5}$ and $Pi_{Residual}$). Rhizospheric soil (soil adhered to the root system, 3 mm) was collected for determination of acid and alkaline phosphatases activity (TABATABAI, 1994) and for microbial carbon (VANCE; BROOKES; JENKINSON, 1987).

At the V12 phenological stage (45 DAS), plant shoots were harvested and roots were collected and washed with deionised water. Then, shoots and roots were oven dried at 60 °C until constant weight, weighed, ground (1 mm sieve) and digested in a mixture (2:1) of HNO_3 and $HClO_4$ (MALAVOLTA; VITTI; OLIVEIRA, 1997). P concentration in plants was determined by inductively coupled plasma optical emission spectrometry (ICP-OES iCAP 7000 series, Thermo Fisher Scientific Inc.). An aliquot of the digested extract was used to measure the ^{32}P activity in a liquid scintillation counter (LS 6000TA, Beckman Coulter Inc.).

As the indirect labelling approach was used, we accounted the plant P contribution from seed since it dilutes the specific activity of P in the plant, leading to underestimation of the plant P derived from fertilizer (Pdff). This procedure is essential in soils with very low P availability and when large seeds are used, as in our case.

To estimate the plant P derived from the seed, we used an adapted approach described by Nanzer et al. (2014). For this, additional pots filled with 5 kg of P-free sand were labelled with ^{32}P (1.76 MBq kg^{-1}) and then, received increasing P levels (as KH_2PO_4 solution) (0, 25, 50, 75 and 100 mg kg^{-1}). The maize cultivation as well as nutrient addition was the same as described before. The Pdff and the fertilizer P recovery were calculated with the equations from Nanzer et al. (2014). Relative agronomic effectiveness (RAE) based on the Pdff or SDW yield (RAE-P and RAE-DW, respectively) were calculated according to Chien, Menon and Billingham (1996), as follows: RAE = $(Y_{OMF} - Y_0) / (Y_{SSP} - Y_0) \times 100$, where Y_{OMF} is SDW yield or Pdff in OMF treatment, Y_{SSP} is SDW yield or Pdff in SSP treatment, and Y_0 is SDW yield or P uptake in the control (no P added).

2.2.4 Statistical analyses

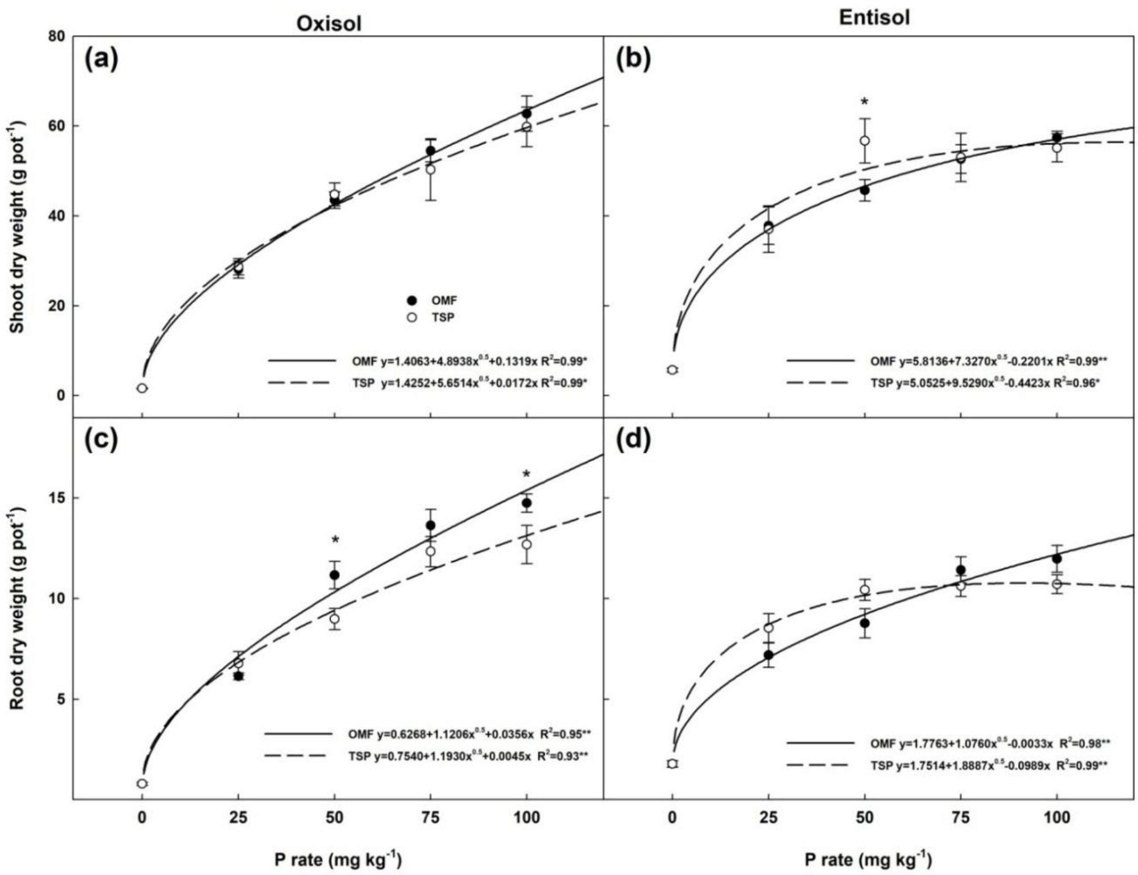
Two-way analysis of variance (ANOVA) at 0.05 level of error probability was performed using the PROC GLM procedure from the Statistical Analysis System - SAS v.9.3 (SAS Inc., Cary, USA). When the F-test was significant, the means of P sourcesand soils were compared by using the least significant difference (LSD), and P doses were ascertained by regression analysis. The square root quadratic model was chosen toassess the plant responses to P rates because it gives remarkably close representationsof the law of diminishing returns (MITSCHERLICH, 1909) compared to exponential and quadratic models (COLWELL, 1994). Moreover, P sources means were contrastedwith the control by Dunnett’s test. The graphs and regression analysis were performed by SigmaPlot (Systat Software, San Jose, CA).

2.3 Results

2.3.1 Plant growth

The shoot and root dry weight production (SDW and RDW, respectively) increased (P< 0.05) with P fertilizer rates in both soils (Figure 2.3). SDW and RDW yields in the control treatment (no P) were much lower than in P fertilized plots. In the Oxisol (Figure 2.3a), no difference between OMF and TSP was observed, while in the Entisol (Figure 2.3b), at 50 mg P kg^{-1}, the yield was higher for TSP than OMF. In the Oxisol, maize root growth was approximately 12% higher with OMF compared to TSP, whereas in the sandy soil, there was no difference.

Figure 2.3 – Shoot dry weight and root dry weight of maize cultivated in two soils (Oxisol and Entisol) with P organomineral fertilizer (OMF) and triple superphosphate (TSP). Asterisk means differences between fertilizers within P rate (LSD's test, P < 0.05). Error bars indicate standard error of mean (n=4)



2.3.2 Phosphatases activity and microbial biomass carbon

As shown in Figure 2.4, the acid and alkaline phosphatases activities (Acid-Pase and Alk-Pase, respectively) in the rhizospheric soil as well as the soil microbial biomass carbon (C_{mic}) were affected (*P*< 0.05) by P sources and P rates in both soils. In the absence of P fertilization, acid phosphatases activity was significantly lower than in the fertilized pots in both soils, but more intensively in the Oxisol (>80% lower) (Figure 2.4a). As expected, the Alk-Pase activity was lower than Acid-Pase. C_{mic} in the Entisol was on average 79.4% lower than in the Oxisol. In general, in the Entisol, application of OMF promoted higher means than TSP for these three parameters. However, in the Oxisol, differences between P sources varied with P rate.

2.3.3 Seed P contribution to total phosphorus uptake

The plant P derived from the seed (Pdfseed) was affected by soils, but there was no difference between OMF and TSP (Figure 2.5). On average, seed P contributed with 1.25% and 0.88% of the total P uptake in P-amended plants in the Oxisol and Entisol, respectively. However, in control plants (no P applied), approximately 7.8% and 54.5% of the total P uptake was derived from the seed, in the Entisol and Oxisol, respectively.

2.3.4 Fertilizer use efficiency

The plant P derived from the fertilizer (Pdff) increased linearly (*P*<0.05) with increasing P rates in both soils (Figures 2.6a and 2.6b), whereas the fertilizer P recovery decreased (Figures 2.6c and 2.6d). In the Oxisol, there was no difference between P sources (Pdff and recovery), but in the Entisol, except at 25 mg kg^{-1}, the TSP source was significantly better than OMF at all P rates (17.4 to 25.7% higher than OMF). Despite these differences between P sources, the P fertilizer recovery in both soils was low, especially in the Oxisol (<23%).

The relative agronomic effectiveness (RAE) for plant biomass production and for Pdff (RAE-DW and RAE-P, respectively) are reported in Table 2.3. In the Entisol, both RAEs were significantly (*P*< 0.05) affected by P sources and P rates. On the other hand, in the Oxisol, only the effect of P rates on RAE-P was observed. In the Oxisol, OMF provided similar or even higher (at 75 and 100 mg kg^{-1}) RAEs than TSP. Although OMF has similar RAE-DW as TSP in the Entisol, the RAE-P was significantly lower compared to TSP at all P levels.

Figure 2.4 – Acid and alkaline phosphatases activity in soil (Acid-Pase and Alk-Pase) and soil microbial biomass carbon (C_{mic}) in two soils (Oxisol and Entisol) cultivated with maize and fertilized with P organomineral fertilizer (OMF) and triple superphosphate (TSP). Asterisk means differences between fertilizers within P rate (LSD's test, $P<0.05$). Error bars indicate standard error of mean (n=4)

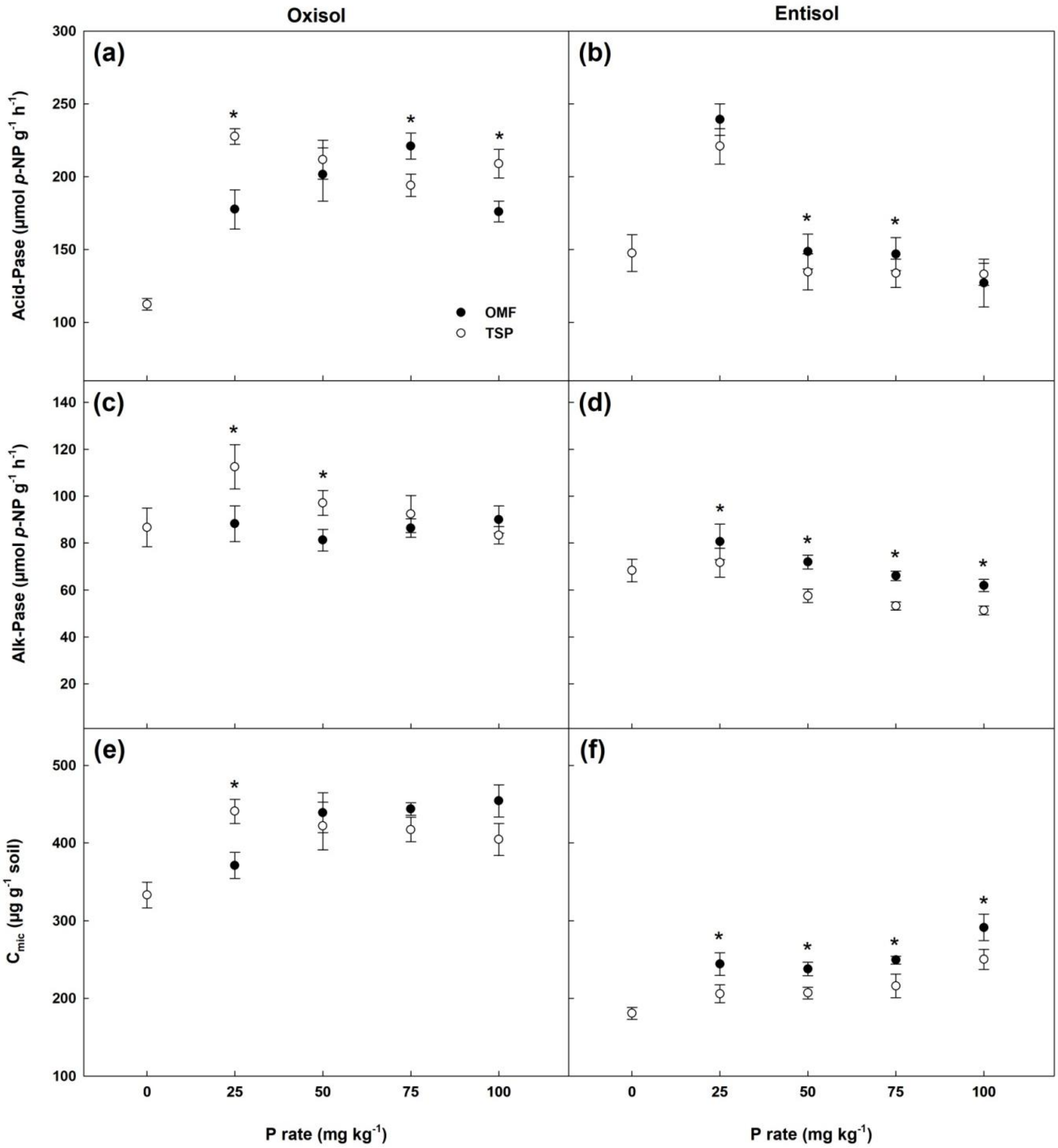


Figure 2.5 – Distribution of plant P derived from fertilizer (Pdff), soil (Pdfsoil), and seed (Pdfseed) in absolute amount and in percentage for the Oxisol and Entisol fertilized with granular organomineral phosphate fertilizer (OMF) or triple superphosphate (TSP)

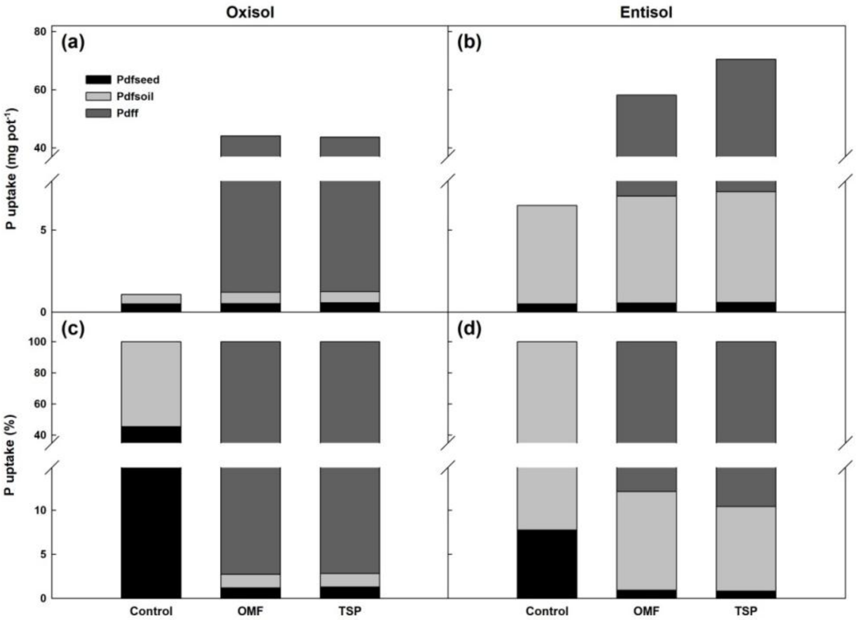


Figure 2.6 – Plant P derived from fertilizer (Pdff) and P recovery from fertilizer by maize cultivated in two soils (Oxisol and Entisol) with P organomineral fertilizer (OMF) and triple superphosphate (TSP). Asterisk means differences between fertilizers within P rate (LSD's test, *P*< 0.05). Error bars indicate standard error of mean (n=4)

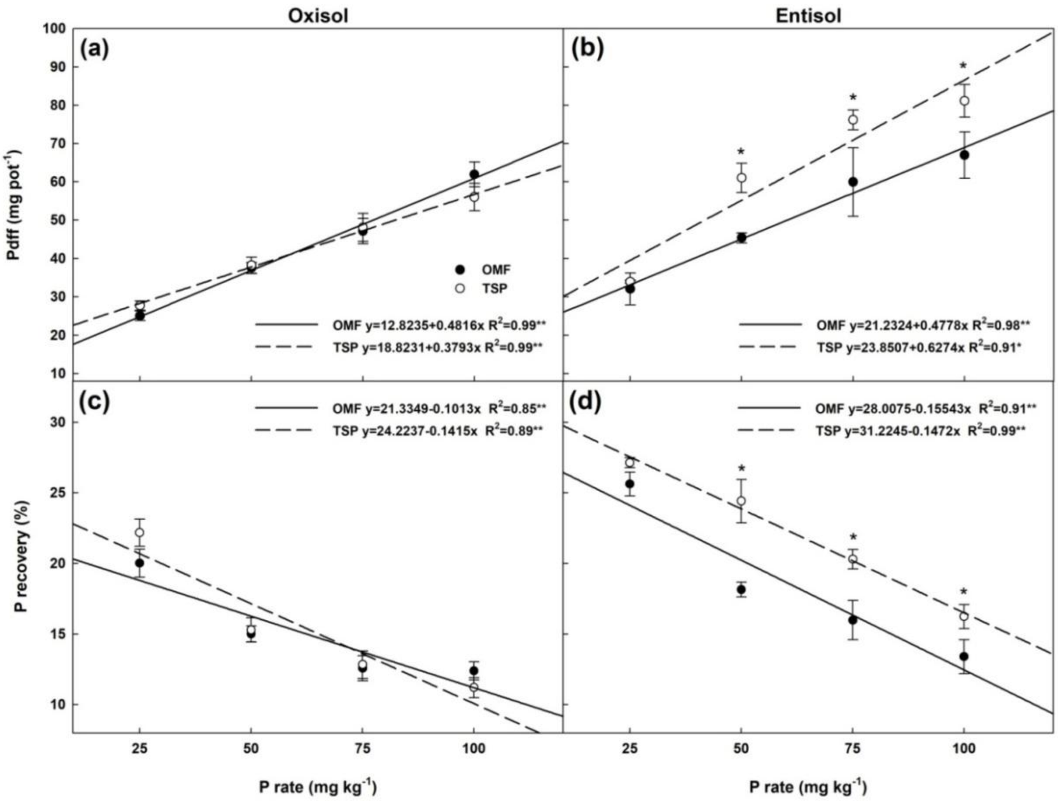


Table 2.3 – Relative agronomic effectiveness for shoot dry weight yield (RAE-DW) and for P derived from fertilizer (RAE-P) as affected by P sources and P rates in two soils

P rate	RAE-DW (%)		RAE-P (%)	
(mg kg^{-1})	TSP	OMF	TSP	OMF
		Oxisol		
25	100	97.71	100	93.24
50	100	97.08	100	98.15
75	100 b	108.64 a	100	97.95
100	100	105.07	100 b	110.75 a
Mean	100	102.13	100	100.03
P source	ns		ns	
P rate	ns		*	
Source x rate	ns		*	
		Entisol		
25	100	102.41	100 a	92.92 b
50	100 a	78.57 b	100 a	70.81 b
75	100	99.24	100 a	76.49 b
100	100	104.6	100 a	80.78 b
Mean	100 a	96.21 b	100 a	80.25 b
P source	*		*	
P rate	*		*	
Source x rate	*		*	

Different letters within column show difference between P source within P rate (LSD's test, $P< 0.05$).*, significant at 0.05 error probability. ns, nonsignificant.

2.3.5Phosphorus fractions in soil

The P sources and P rates significantly affected the labile and moderately labile P pool in the Entisol, whereas in the Oxisol, we observed only the effect of P rates (Figure 2.7). Non-labile P fractions were affected by neither P rates nor P sources, in both soils (Figure 2.7 and Table 2.6). The phosphate fertilization in both soils significantly increased the labile and moderately labile P forms compared to the control treatment (Tables 2.4 and 2.7).

Approximately 87.3% and 53.1% of the soil P stock (total P) was represented by non-labile P fraction in the Oxisol and in the Entisol, respectively. In the Oxisol, the labile and moderately labile P pool contributed approximately 3% and 9.5% of soil total P, whereas in the Entisol, we observed a higher contribution of these P pools (18.8 and 28.2%, respectively).

Readily available P for plants (Pi_{AER}) was higher in plots fertilized with OMF than TSP in the Oxisol, but in the Entisol, Pi_{AER} was higher when TSP was applied. Even though the inorganic labile P fractions (Pi_{AER} and Pi_{Bic}) were higher with TSP application, the organic labile P forms in the Entisol were approximately 85% higher with OMF. A similar trend was observed for the moderately labile P fractions (Table 5, Entisol), except for the Pi_{HCl} fraction. There was no difference between P sources for all moderately labile P fractions in the Oxisol. Soil total P was significantly higher with TSP application than OMF (Entisol), although no difference was observed in the Oxisol.

Figure 2.7 – Labile, moderately labile and non-labile phosphorus in two soils (Oxisol and Entisol) as affected by P rates and P doses. Asterisk means differences between P sources within P rate (LSD's test, *P*< 0.05). Error bars indicate standard error of mean (n=4)

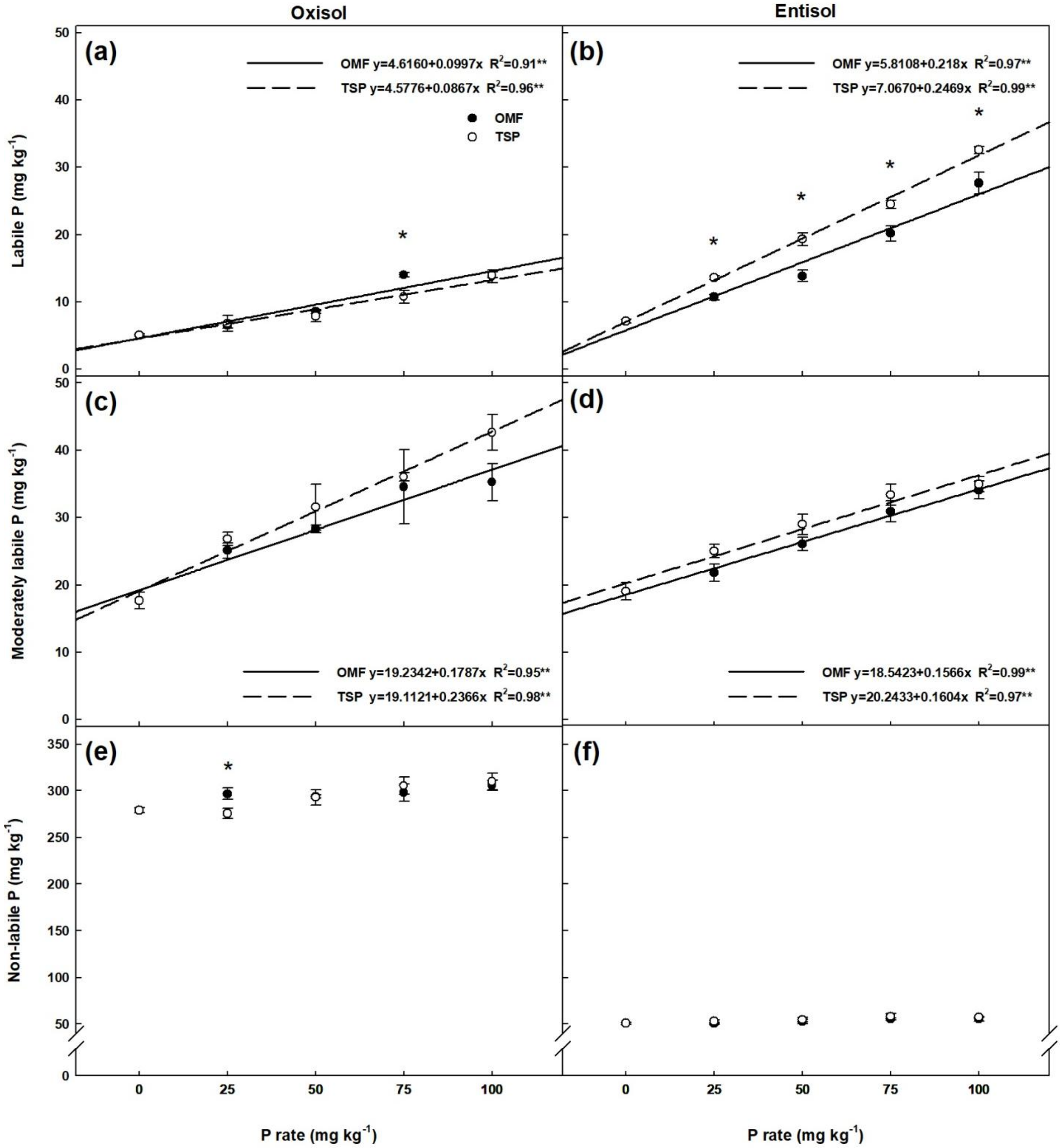


Table 2.4 –Labile P fractions levels (mg kg^{-1}) under two P sources (organomineral fertilizer (OMF) and triple superphosphate (TSP)) and five P rates

P rate (mg kg^{-1})	P_{AER}		Pi_{Bic}		Po_{Bic}	
	OMF	TSP	OMF	TSP	OMF	TSP
			Oxisol			
Control	0.31		1.07		3.74	
25	0.77	0.48	2.93	2.93	2.81	3.41
50	1.55 a	0.67 b	4.27	4.77	2.72	2.44
75	2.87 a	1.25 b	8.67	6.97	2.47	2.53
100	2.96 a	2.24 b	8.50 b	10.78 a	2.37	0.96
Source	*		ns		ns	
Rate	*		*		ns	
Source x Rate	*		ns		ns	
Control vs. factorial §	*	*	*	*	*	*
			Entisol			
Control	0.66		2.69		3.77	
25	2.65	3.55	4.51	5.53	3.58 b	4.52 a
50	4.22 b	6.74 a	5.44 b	9.99 a	4.18 a	2.57 b
75	7.43	8.97	8.32 b	14.31 a	4.41 a	1.20 b
100	12.19 b	14.19 a	10.83 b	17.56 a	4.63 a	0.79 b
Source	*		*		*	
Rate	*		*		*	
Source x Rate	ns		*		*	
Control vs. factorial	*	*	*	*	ns	*

§ Differ from the control by Dunnett's test (P< 0.05). *, significant at 0.05 error probability. ns, nonsignificant. Different letters within the same P rate show differences by LSD’s test (P< 0.05).

Table 2.5 –Moderately labile P fractions levels (mg kg^{-1}) under two P sources (organomineral fertilizer (OMF) and triple superphosphate (TSP)) and five P rates

P rate (mg kg^{-1})	$Pi_{NaOH-0.1}$		$Po_{NaOH-0.1}$		Pi_{HCl}	
	OMF	TSP	OMF	TSP	OMF	TSP
			Oxisol			
Control	5.82		11.82		0.01	
25	10.29	8.99	14.78	17.83	0.01	0.02
50	11.75	13.66	16.54	17.88	0.02	0.02
75	15.26	15.92	19.26	20.08	0.02	0.04
100	15.77 b	22.44 a	19.46	20.11	0.03 b	0.07 a
Source	*		ns		ns	
Rate	*		ns		ns	
Source x Rate	*		ns		ns	
Control vs. factorial §	*	*	*	*	ns	ns
			Entisol			
Control	11.75		6.60		0.70	
25	15.26	15.41	5.76 b	8.56 a	0.75 b	1.02 a
50	16.57 b	21.74 a	8.50 a	6.17 b	0.99	1.07
75	20.54 b	26.81 a	9.12 a	5.47 b	1.23	1.09
100	23.30 b	28.67 a	10.02 a	5.52 b	0.75	0.73
Source	*		*		ns	
Rate	*		ns		*	
Source x Rate	*		*		*	
Control vs. factorial	*	*	*	ns	*	*

§ Differ from the control by Dunnett's test (P< 0.05). *, significant at 0.05 error probability. ns, nonsignificant. Different letters within the same P rate show differences by LSD’s test (P< 0.05).

Table 2.6 – Non-labile P fractions levels (mg kg^{-1}) and soil total P under two P sources (organomineral fertilizer (OMF) and triple superphosphate (TSP)) and five P rates

P rate (mg kg^{-1})	$Pi_{NaOH-0.5}$		$Po_{NaOH-0.5}$		$Pi_{Residual}$		Total P ¤	
	OMF	TSP	OMF	TSP	OMF	TSP	OMF	TSP
				Oxisol				
Control	14.11		3.94		261.13		391.96	
25	13.82	13.94	5.18	5.35	277.51	256.25	328.10	309.19
50	12.77	13.55	4.57	5.61	275.77	273.80	329.95	332.55
75	14.11	13.27	3.54	5.79	280.30	286.23	347.26	352.08
100	14.11	14.53	4.71	4.94	286.93	290.41	354.87	366.48
Source	ns		ns		ns		ns	
Rate	ns		ns		ns		*	
Source x Rate	ns		ns		ns		ns	
Control vs. factorial §	ns	ns	ns	ns	ns	ns	*	*
				Entisol				
Control	5.67		6.44		38.70		77.24	
25	5.96	6.21	6.56	6.30	38.12	40.44	82.00 b	92.75 a
50	5.67	6.55	6.45	6.81	40.09	41.14	91.99 b	102.78 a
75	6.30	7.14	6.88	6.93	42.18	43.93	106.41 b	115.85 a
100	6.30	6.47	7.30	7.25	41.49	43.58	114.66 b	124.76 a
Source	ns		ns		ns		*	
Rate	ns		ns		ns		*	
Source x Rate	ns		ns		ns		ns	
Control vs. factorial	ns	*	ns	ns	ns	ns	*	*

§ Differ from the control by Dunnett's test (P< 0.05). *, significant at 0.05 error probability. ns, nonsignificant. Different letters within the same P rate show differences by LSD's test (P< 0.05).

2.4 Discussion

OMF had a similar agronomic effectiveness as the reference P source (TSP) in the Oxisol, but TSP was greater than OMF in the Entisol (Table 2.3). Differences in the efficiency between these P sources might be related to the maximum P adsorption capacity (MPAC) of the studied soils (Table 2.2) as well as by the solubility of these two P sources (Table 2.1). Since OMF has a lower P solubility than TSP, in the Entisol (which has a very low MPAC), the soil P availability was higher with TSP, resulting in higher plant growth as well as higher P fertilizer recovery and RAE-P. However, in the high P adsorbing Oxisol used in this study, the higher P solubility of TSP resulted in similar or higher proportion of less available P fractions for plants (Figure 2.7 and Tables 2.4-2.6) and similar agronomic efficiency between P sources. Furthermore, the significant contribution of seed P to the total P uptake by control plants (up to 54.5%) shows the importance of taking into account the Pdfseed when the indirect ^{32}P-labelling method is used, in order to not underestimate the Pdff.

2.4.1 Plant responses to P fertilizer application

The maize growth increased significantly with P fertilizer addition as a result of very low initial P availability in the selected soils (Table 2.2). There was no difference in shoot dry weight (SDW) between TSP and OMF in both soils, but higher responses to P fertilization were observed in the Oxisol, which is directly linked to its much higher MPAC (Table 2.2). These results are supported by the higher root production in the Oxisol than the Entisol (Figures 2.3c and 2.3d), which led to an increase of the root:shoot ratio, a common response of plants to restricted P availability conditions (LYNCH, 2007). Furthermore, application of organic matter in soil stimulates root growth (DOBBSS et al., 2007; NARDI et al., 2002). This process might explain the higher root biomass produced with OMF than TSP in the Oxisol. Nevertheless, in the Entisol, where P availability is less restricting to plants compared to the Oxisol, this effect was less intense.

Significant differences of plant P derived from fertilizer (Pdff) and P recovery index between soils were observed, confirming our initial hypothesis that soil MPAC influences the P fertilization efficiency. In the soil with very high MPAC (Oxisol), there was no difference between OMF and TSP at all P rates (Figures 2.6a and 2.6c), but in the Entisol, TSP promoted significantly higher Pdff and P recovery compared to OMF (Figures 2.6b and 2.6d). In agreement with our results, Sakurada et al. (2016), using a clayey Oxisol, found that maize SDW and plant P uptake did not vary with application of mineral fertilizer mix or OMFs in the first cropping cycle, although mineral P fertilizer was greater than granular OMF at the highest P level (200 mg kg^{-1}). However, these authors reported a significantly lower P uptake (accumulated in four successive cropping cycles) with granular OMF compared to mineral fertilization. Other authors have also reported no differences between mineral or organomineral fertilizers on yields of maize, wheat and sugarcane (ANTILLE et al., 2017; CORRÊA et al., 2016; TEIXEIRA; SOUSA; KORNDÖRFER, 2014).

Besides soil MPAC, another aspect that contributed to these results is the solubility of the fertilizers (Table 2.1), since approximately 83% of the total P in TSP is water soluble whereas OMF is only about 50%. This characteristic gives OMF a slow P release property, as reported by Sakurada et al. (2016). Since the Entisol has much lower MPAC than the Oxisol and TSP is more soluble, higher plant P uptake and consequently higher P recovery in the Entisol are expected, since P adsorption losses are much lower than in the Oxisol. These results were confirmed by the higher labile P fractions, which are discussed later in the subtopic *Effect of P fertilization on soil P fractions*.

Although OMF had a lower relative agronomic effectiveness for SDW and for Pdff (RAE-DW and RAE-P, respectively) in the Entisol, it is worth mentioning that most tropical soils are highly weathered like the Oxisol used in this study, where OMF had a similar RAE-DW and RAE-P. Thus, our findings show the agronomic viability of using OMF as a source of P, contributing to reduce the dependence on finite mineral P resources and at the same time lower the disposal of poultry litter, which is an important environmental benefit.

2.4.2 P fertilization effects on phosphatases activity and microbial biomass carbon

We also observed the effect of P sources on the microbial biomass carbon (C_{mic}) and Pases activity in the two soils (Figure 2.4). In the sandy soil (Entisol), the means of the parameters were higher when the plots were fertilized with OMF at all P rates, but no clear trend was observed, since the difference between P sources varied with P rates.

The microbial biomass growth depends on soil parameters such as moisture, texture, temperature, pH and nutrient availability (WARDLE, 1992). Among the nutrients, carbon (C) is the most limiting for microbial growth, followed by nitrogen (N) and phosphorus (P) (TORTORA; FUNKE; CASE, 2016). These findings are supported by our results, since the C_{mic} in the control (no P) was significantly lower than the P fertilized plot, due to the very low P and C availability in both soils (Table 2.2). Similar results have been reported (CHU et al., 2007; LIU et al., 2012; ZHONG; CAI, 2007). Additionally, higher C_{mic} with OMF than TSP could be caused by C input through OMF application. Other authors have also observed higher C_{mic} in soil treated with organic manures (CHU et al., 2007; SINGH et al., 2015). Higher C_{mic} with TSP at 25 mg kg^{-1} in the Oxisol most likely occurred due to the higher solubility of this P source, which lead to greater soil P bioavailability attenuating the high MPAC of this soil. The lower C_{mic} in the Entisol compared to the Oxisol could be due to texture and moisture (VENZKE FILHO et al., 2008; WARDLE, 1992).

Both acid and alkaline phosphatases activities were affected by P rates (Figures2.4a-d). The much higher Pases activity in P amended plots correlated positively with the higher C_{mic}(Figure 2.4e-f) and P availability in soil (Table 2.4), confirming that P limited microbial growth and that Pases activity has a higher microbial contribution than roots. Mandal et al. (2007) also observed a significant correlation between C_{mic} and Pases activities. In the Oxisol, at the lowest P rate (25 mg kg^{-1}), higher Pases activities with TSP than OMF was the result of significantly lower labile P fractions (Table 4). Despite the increasing P rates in this study, the Pases activities were reduced. This result can be explained by the reduction of on the microbial and roots strategies to mobilize soil P, such as through organic acid exudation and extracellular Pases (CARVALHAIS et al., 2011; RICHARDSON et al., 2011). In the Entisol, we observed lower Pases activities compared to the Oxisol, mainly related to the higher available P forms (Figures 2.7a-b and Table 2.4) and lower C_{mic} (Figures 2.7e-f).

2.4.3 Effect of P fertilization on soil P fractions

The labile and moderately labile P pools were affected by soils, P sources and P rates (Figure 2.7). Overall, the labile P pool was larger in the sandy soil (Entisol) compared to the Oxisol, whereas for the moderately labile P pool, the opposite occurred. Non-labile P is the major pool in both soils and contributed 87% and 53% of the total P stock in the Oxisol and Entisol, respectively. However, there was no difference between P sources, in agreement with Olibone and Rosolem (2010). This large difference between the soils can be attributed to their mineralogical composition, where the Oxisol contains significantly higher amounts of iron and aluminium oxides such as hematite, gibbsite and kaolinite, giving very high P adsorption capacity (MULJADI; POSNER; QUIRK, 1966; PARFITT, 1989). Predominance of non-labile P forms in very weathered tropical soils such as Oxisols has been reported (CHERUBIN et al., 2016; RODRIGUES et al., 2016).

Although non-labile P is the major P pool in both soils, by comparing P fertilized and unfertilized plots (control), we found that only about 7% of the non-labile P came from P fertilization. Although P is strongly adsorbed on the surface of iron and aluminium oxides, the formation of binuclear surface complexes is a slow reaction (ATKINSON; PARFITT; SMART, 1974; PARFITT; ATKINSON; SMART, 1975) and is intensified at low pH (ACELAS et al., 2013; ELZINGA; SPARKS, 2007). Thus, the contribution of P fertilizer addition to the non-labile P pool might increase with time (NEGASSA; LEINWEBER, 2009) and might be much higher in the Oxisol, which has very high MPAC. Nevertheless, in short-term studies like this, low or insignificant changes in non-labile P pool are expected.

Phosphorus fertilization increased the labile and moderately labile P pools by approximately 1.3% and 3.6% (Oxisol) and 9.2% and 3.5% (Entisol), respectively. Even though the clay fraction of the Entisol contains the same strong P adsorbents found in the Oxisol, this was not the main factor controlling the behaviour of the soil P derived from the fertilizer, since the clay fraction represented only about 6% of total soil texture (Table 2.2). Although there was no difference between P sources on the plant P uptake in theOxisol (Figure 2.6), significantly higher amounts of readily available P (Pi_{AER} fraction) was obtained with OMF than TSP, whereas in the sandy soil (Entisol), the opposite was observed (Table 2.4). These results can be attributed to the distinct MPAC of the selected soils as well as the effect of higher water solubility of TSP than OMF. These findings show that OMF promotes better maintenance of soil P phytoavailability than TSP, which could improve crop yields, P use efficiency in highly weathered soils and also reduce P losses (e.g., leaching) in sandy soils, as reported by Kang et al. (2011) and by Elliott, O'connor and Brinton (2002).

In the Entisol fertilized with TSP, only 9% of the labile P pool was found in organic P forms, against 23% with OMF, but this proportion can be even lower (for TSP) or higher (for OMF) by increasing P rates. On the other hand, in the Oxisol, no difference was observed in the organic labile P pool between OMF (24%) and TSP (23%). This different behaviour of P in this soil might be related to the lower microbial P immobilization and lower Pases activities (Figure 2.4) in the Entisol, which directly affects the rate of organic P mineralization in soil (RICHARDSON et al., 2011). Additionally, the higher amount of inorganic labile P forms in the Entisol contributed to a lower proportion of organic P forms compared to the Oxisol, as a result of contrasting soil P adsorption between these soils.

Moderately labile P forms varied significantly between soils (Figure 2.7 and Table 2.5). The higher proportion of moderately labile P forms in the Oxisol compared to the Entisol is the result of higher MPAC of the Oxisol. In agreement with recent studies (RODRIGUES et al., 2016; ROSOLEM; MERLIN, 2014), we found the most moderately labile P pool to be dominated by P bound to iron and aluminium oxides ($Pi_{NaOH-0.1}$ and $Po_{NaOH-0.1}$), accounting for approximately 99.9% and 97.7% in the Oxisol and Entisol, respectively. The portion of moderately labile calcium bound P (Pi_{HCl} fraction) was affected by neitherP sources nor P rates (Table 2.5). Low Pi_{HCl} concentration in both soils shows a natural low content of calcium phosphate minerals (e.g., apatite) as a result of intense weathering processes. Although calcium phosphate is also formed through precipitation processes

(LINDSAY, 1979), an insignificant amount was formed, since the soil pH at the end of the experiment was not alkaline. On average the pH values were 5.8 and 5.6 in the Oxisol and Entisol, respectively (data not shown).

It is known that soil pH affects the P phytoavailability due to P adsorption reactions on the surface of soil minerals (BARROW, 1986; PARFITT; ATKINSON; SMART, 1975). In a recent study, Jokubauskaite et al. (2015) reported a significantly higher amount of Fe/Al phosphate in an acid soil (pH=4.2) than a slightly neutral soil (pH=6.7). The absence of difference between OMF and TSP may be an effect of soil pH, since at slight acidity the speed and strength of P adsorption reaction is relatively lower. Furthermore, soil acidity also affects the surface charge of organic groups such carboxyl (GONDAR et al., 2005) found in OMF granules. At lower pH, organic groups are protonated, resulting in stronger affinity attraction by P in the OMF granules. However, the binding energy is much weaker compared to inner-sphere surface complexes formed on the surface of Fe/Al oxides (e.g., goethite), which may not affect the plant P uptake. Thus, our findings suggest that OMF is promising to improve the P fertilization efficiency in highly weathered and acid soils, by reducing P adsorption losses.

2.5 Conclusions

Soil P adsorption capacity affects significantly the effectiveness of P sources.

In highly weathered soils, granular OMF is as effective as conventional P fertilizers, and soil P fractions are controlled by soil P adsorption capacity.

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3 A POULTRY LITTER-DERIVED ORGANOMINERAL PHOSPHATE FERTILIZER HAS HIGHER AGRONOMIC EFFECTIVENESS THAN CONVENTIONAL PHOSPHATE FERTILIZER APPLIED TO MAIZE AND SOYBEAN

Abstract

Inadequate disposal of organic wastes like poultry litter (PL) may promotes eutrophication of water bodies due to its high nutrients content including phosphorus (P). Thus, recycle P from PL to produce organomineral fertilizer (OMF) besides reduces the dependence on finite mineral P reserves 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 (*Zea mays* L.) and soybean (*Glycine max* L.) in a highly weathered tropical soil (RhodicHapludox). OMF was compared to single superphosphate (SSP) at five increasing P rates between 0 and 70 kg P 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. Similar trend was observed for soil P availability and P uptake. The leaf P content and soil pH was affected by neither P sources nor P rates. Despite of there was no difference between granular OMF and SSP on the crop yields, OMF had a significantly higher relative agronomic effectiveness (RAE) based on the SDW. Moreover, OMF had a RAE based on the P uptake 50.7% higher than SSP in maize and a RAE based on the grain yield 25.8% higher than SSP in soybean. These results show that the production of granular OMF from PL is viable alternative to substitute totally conventional P fertilizers and reduces the dependence of mineral P reserves.

Keywords: *Zea mays* L., *Glycine max*L., single superphosphate, SSP, OMF, available phosphorus, recycling fertilizer, weathered soil, Oxisol

3.1 Introduction

The world poultry meat production is approximately 89.6 million tonnes (USDA, 2017) which generates annually over 68 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 whether inadequate disposed on the soil surface is often reported to cause serious environmental problems like eutrophication of water bodies (CORRELL, 1998;

SCHROEDER; RADCLIFFE; CABRERA, 2004; SHARPLEY, 1997). Recycle P from organic wastes like 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 recycle 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 balanced amount of nutrients, complementary fertilizations are needed to supply the nutrient demand for crops, resulting in a higher cost associated to 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 (ANTILLE; SAKRABANI; GODWIN, 2014; KIEHL, 2008; SAKURADA et al., 2016). Furthermore, OMFs has been reported to preventing N losses from soil by leaching (FLORIO et al., 2016).

The slow-release property of OMFs (CARDOSO et al., 2017; SAKURADA et al., 2016) may also reduce P losses by adsorption reactions on surface of 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 (SYERS; JOHNSTON;CURTIN, 2008). However, Deeks et al. (2013) and Morais and Gatiboni (2015) observed nodifference between OMFs and conventional mineral fertilizers on P availability in soil.

Response of crops to application of OMFs produced from different organic wastes has been evaluated (CORRÊA et al., 2016; KOMINKO; GORAZDA;WZOREK, 2017; MAZEIKA; STAUGAITIS;BALTRUSAITIS, 2016; OLIVEIRA et al., 2017; OLIVÉRIO et al., 2011; RAO et al., 2007). For instance, Deeks et al. (2013) 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, Sousa and Korndörfer (2014) in sugarcane. However, in a more recent study, Antille et al. (2017) 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, this field study was carried out to evaluate the agronomic effectiveness of a granular organomineral P fertilizer produced from PL applied to maize and soybean in a highly weathered tropical soil.

3.2 Material and methods

3.2.1 Production of granular organomineral phosphate fertilizer

The production of the granular organomineral fertilizer is following described: - First, both organic (poultry litter, PL) and mineral (monoammonium phosphate, MAP) P sources 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 and then, homogenously mixed in an industrial mixer with bentonite (2%). The OMF granules was produced using granulator with a 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 3.1) according to the methodology described in Brasil (2014).

Table 3.1 – Chemical composition of treatments

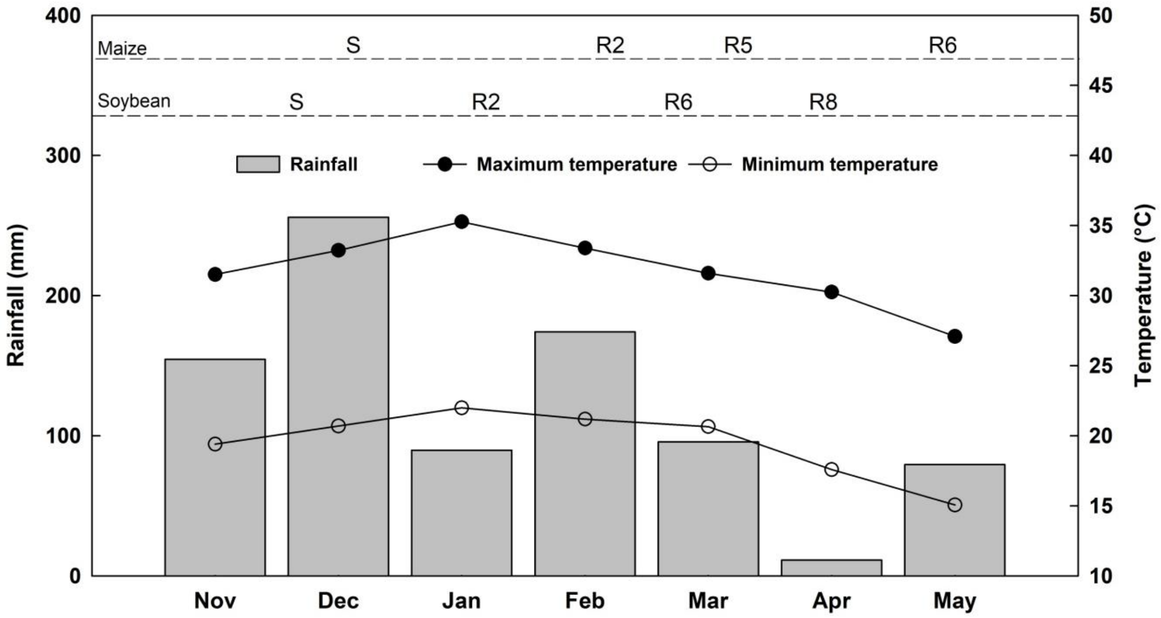
Parameter	OMF_m	OMF_s	SSP
pH (0.01 M $CaCl_2$)	5.9	5.9	2.7
Organic carbon (%)	24.53	23.34	0
C:N ratio	4.34	3.87	-
P_{total} (%)	23.93	20.8	18.77
P_{water} (%)	12.62	13.31	10
P_{NAC} (%)	18.8	19.85	18
N_{total} (%)	5.65	6.03	0
K_2O (%)	2.09	2.14	0
B (mg kg^{-1})	12	9	0
Cu (mg kg^{-1})	199	62	27
Mn (mg 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

SSP, single superphosphate. OMF, organomineral fertilizer. OMF_m, OMF used in the experiment with maize.OMFs, OMF used in the experiment with soybean.P_{NAC}, P soluble in neutral ammonium citrate plus water.P_{AC}, P soluble in 2% citric acid.

3.2.2 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, the climate is Cwa. The monthly rainfall, maximum and minimum air temperatures during the experiment are shown in the Figure 3.1. The soil was classified as a clayey Rhodic Hapludox(SOIL SURVEY STAFF, 2014) and was chemically and physically characterized (Table 3.2) according to the methodology proposed by van Raij et al. (2001) and Bouyoucos (1926), respectively. The selected soil has a high phosphate adsorption capacity (Table 3.2 and Figure 3.2) which is supported by the presence of strong P adsorbents (e.g. hematite, gibbsite and kaolinite), as revealed by X-ray diffraction analysis (Figure 3.3).

Figure 3.1 – 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



3.2.3 Experimental setup

To assess the agronomic effectiveness of OMF compared to conventional P fertilizer (single superphosphate, SSP), two simultaneous field experiments were carried out during the 2014/2015 season (maize and soybean). The experimental design was a randomized complete block with 2x4+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.

Table 3.2 – Chemical and physical properties of a clayey Rhodic Hapludox

Property	Mean
pH (0.01 M $CaCl_2$)	5.0
Organic matter (g kg^{-1})	46
Resin P (mg kg^{-1})	12
Maximum P adsorption capacity (mg kg^{-1})	1691.4
Exchangeable Ca^{2+} ($mmol_c kg^{-1}$)	40
Exchangeable Mg^{2+} ($mmol_c kg^{-1}$)	22
Exchangeable K^+ ($mmol_c kg^{-1}$)	3.5
H^+ + Al^{3+} ($mmol_c kg^{-1}$)	38
Zinc (mg kg^{-1})	1.2
Sulphate (mg kg^{-1})	3
Cation exchange capacity ($mmol_c kg^{-1}$)	103.5
Base saturation (%)	63
Clay (g kg^{-1})	694
Silt (g kg^{-1})	6
Sand (g kg^{-1})	300

Figure 3.2– Maximum phosphate adsorption capacity (MPAC) of a clayey RhodicHapludox as adjusted to the Langmuir isotherm

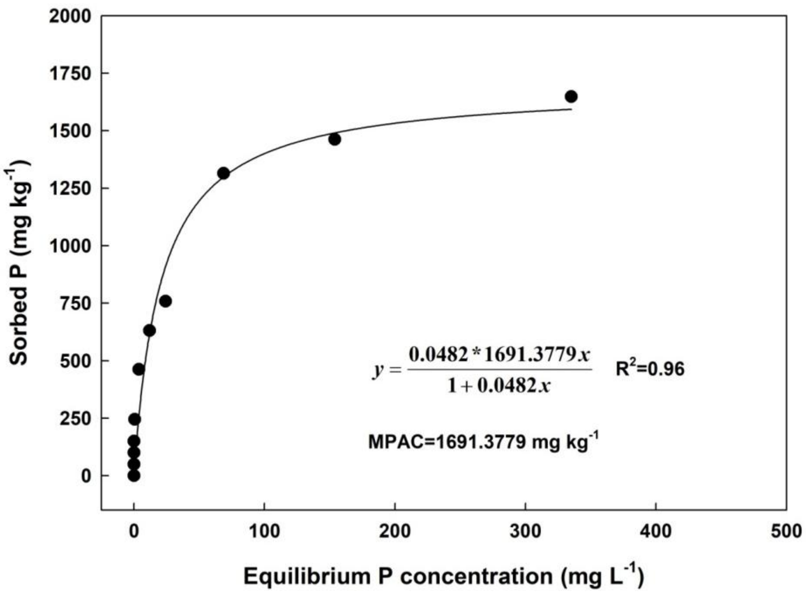
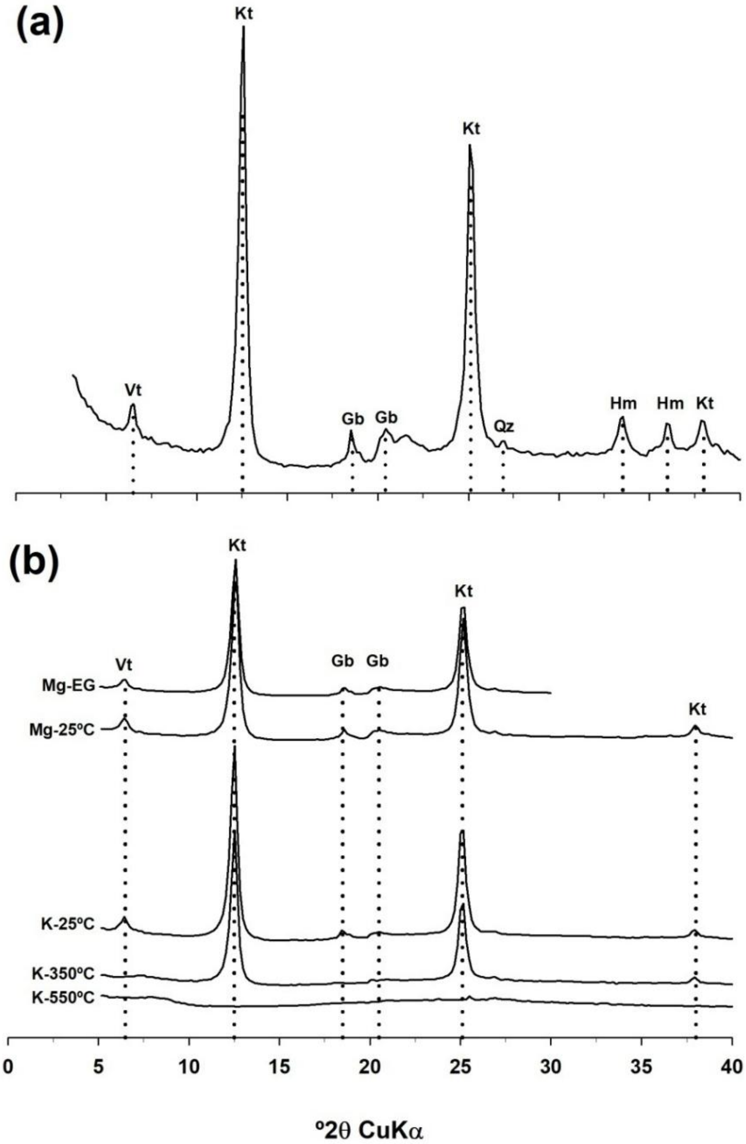


Figure 3.3 – X-ray diffractograms of non-deferrified (A) and deferrified (B) clay fraction at room temperature (K-25°C), K^+ heated at 350°C and 550°C (K-350°C and K-550°C, respectively), Mg^{2+} at room temperature (Mg-25°C) and Mg^{2+} solvated with ethylene glycol (Mg+EG). Gibbsite (Gb), Hematite (Hm), Kaolinite (Kt), Quartz (Qz) and Vermiculite (Vt)



Three months before the maize sowing, lime was applied to raise the soil base saturation to 70% (VAN RAIJ et al., 1997) and incorporated with conventional tillage. Liming was not necessary for the soybean area since the soil base saturation (Table 3.2) was considered adequate for soybean (VAN RAIJ et al., 1997). 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®) was 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. (1997). 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 3.1) and on the P rate.

3.2.4 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 (full bloom)(FEHR et al., 1971) and maize (blister stage)(ABENDROTH et al., 2011) (50 and 65 DAS, respectively). Leaf samples for nutritional diagnosis were collected according to procedure described by Malavolta, Vitti and Oliveira (1997). 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, weighed for shoot dry weight (SDW) determination. Plant and leaf samples were ground (1 mm sieve) and digested in a mixture (2:1) of HNO_3 and $HClO_4$(MALAVOLTA; VITTI;OLIVEIRA, 1997). 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, 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 $CaCl_2$) were determined according to van Raij et al. (2001). 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).

3.2.5 Grain yield measurement and calculations

The harvest of maize and soybean was performed at the physiological maturity, corresponding to the R8 and R6 phenological stage of soybean and maize, respectively (ABENDROTH et al., 2011; FEHR et al., 1971). The grain yield was determined by manually 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 were 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, Menon and Billingham (1996), 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).

3.2.6 Statistical analyses

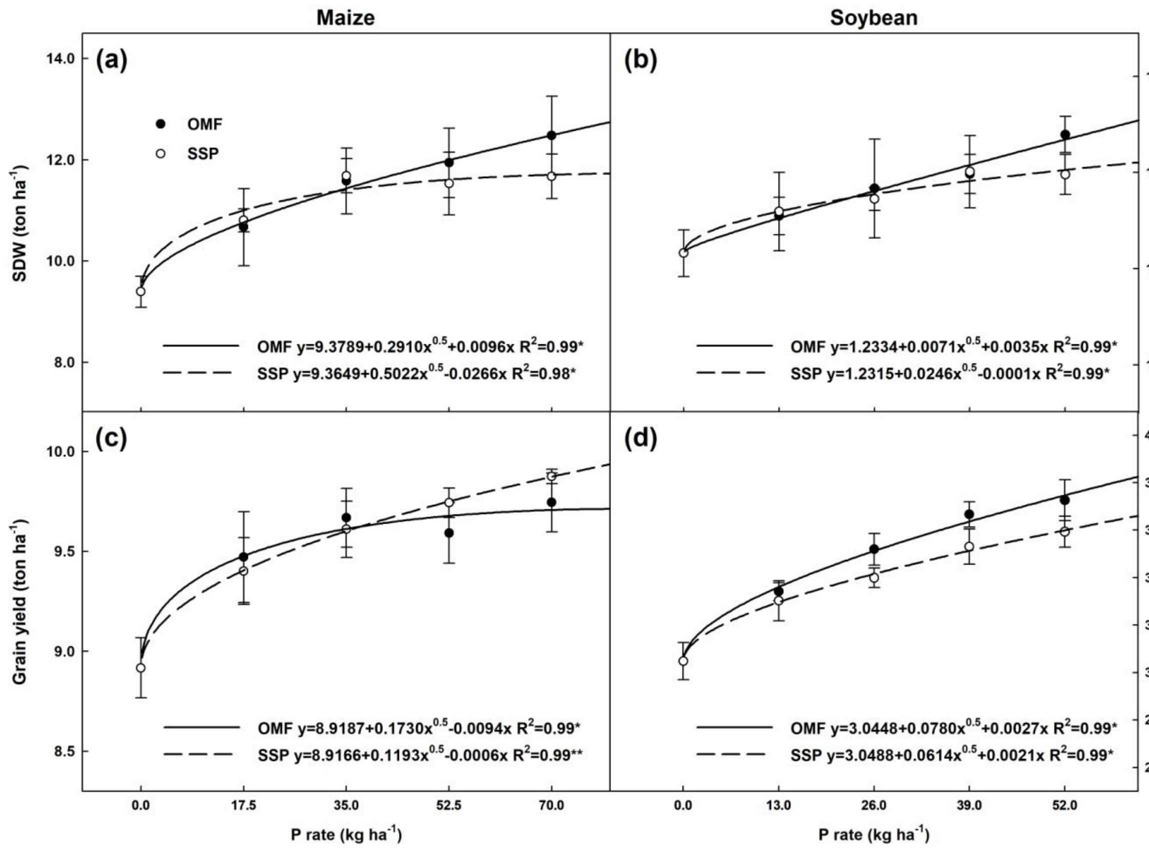
A two-way analysis of variance (ANOVA) at 0.05 level of error probability was performed using the PROC GLM procedure from the Statistical Analysis System - SAS v.9.3 (SAS Inc., Cary, USA). When the F test was significant, the means of P sources were compared by using the least significant difference (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 (MITSCHERLICH, 1909) compared to exponential and quadratic models (COLWELL, 1994). Moreover, P sources means were contrasted with the control by Dunnett’s test. The graphs and regression analysis were performed by SigmaPlot v.10.0 (Systat Software, San Jose, CA).

3.3 Results

3.3.1 Plant growth and grain yield

Shoot dry weight (SDW) and grain yields of soybean and maize increased significantly with increasing P rates, however, no difference between OMF and SSP was observed at all P rates (Figure 3.4). 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, 22.9% and 8.1% higher in P-amended plot compared to the control, respectively. With respect to soybean, P fertilization increased approximately 11.7% and 15.1% the SDW and grain yields, respectively.

Figure 3.4 – 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)

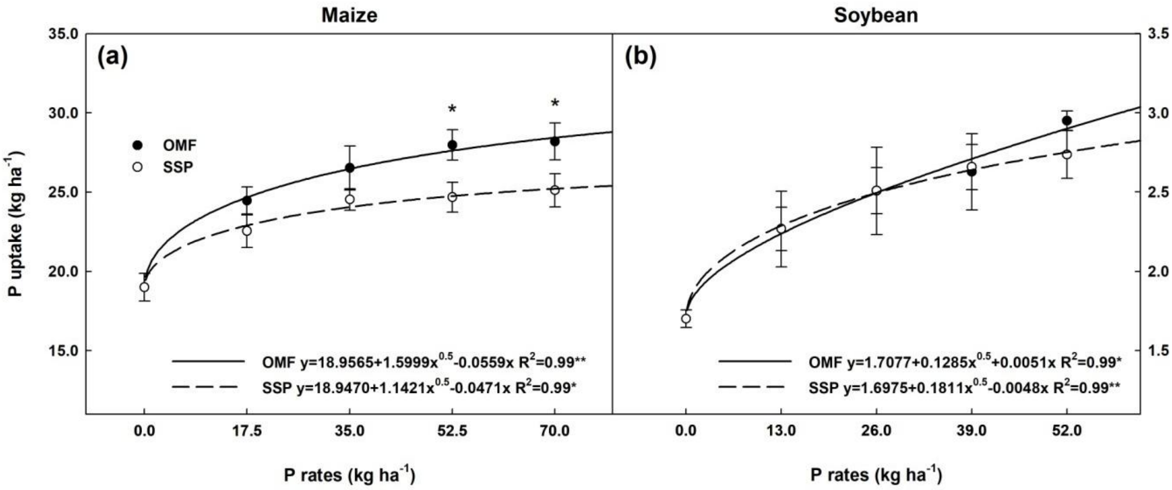


3.3.2 Fertilizer-phosphorus uptake and nutritional status

P uptake by both maize and soybean increased significantly with increasing P rates (Figure 3.5). 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.

The P concentration in soybean leaves was affected by neither P sources nor P rates (Figure 3.6b). With respect to maize (Figure 3.6a), there was effect of P rates, despite 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 3.5 – 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, P< 0.05). Error bars indicate standard error of mean (n=4)



3.3.3 Soil test phosphorus and soil pH

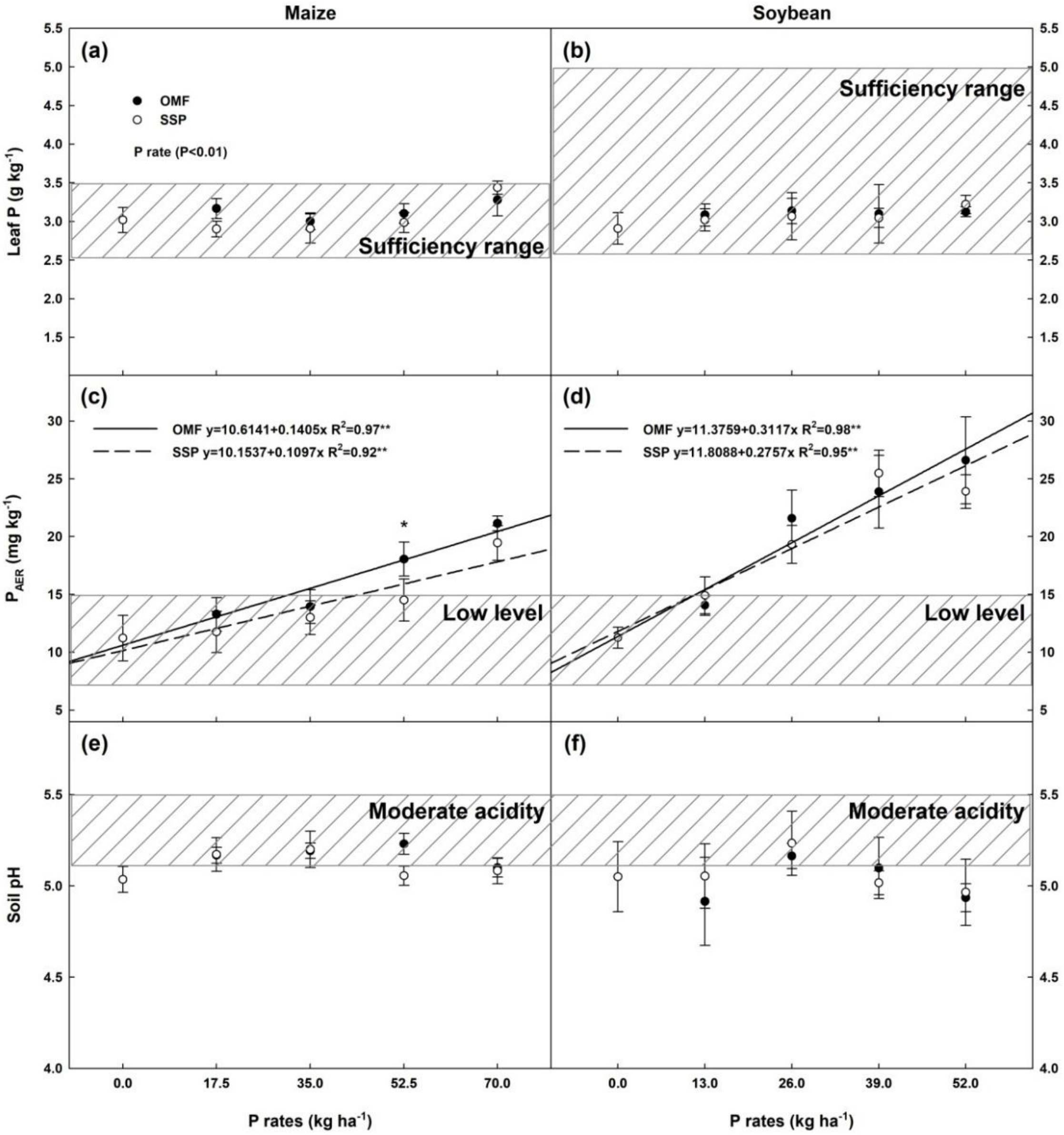
Soil P extracted by anion-exchange resin (P_{AER}) increased linearly with P rates for both crops (Figures 3.6c and 3.6d). P_{AER} ranged from 11.26 to 21.14 mg kg^{-1} (maize) and from 11.25 to 26.60 mg kg^{-1} (soybean) which resulted in a higher slope in soil cultivated with soybean than maize. There 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<0.05) 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 3.6e and 3.6f). Soil pH ranged from 5.04 to 5.23 and from 4.92 to 5.23 in soil cultivated with maize and soybean, respectively.

3.3.4 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, excepted RAE-GY (maize) and RAE-P (soybean), which was not affected by P sources.

For maize, OMF promoted approximately 11.4% and 50.7% higher RAE-DW and RAE-P in relation 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 22.74% greater than SSP.

Figure 3.6 – 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, *P*< 0.05). Error bars indicate standard error of mean (n=4)



With respect to soybean, OMF had a higher RAE-DW and RAE-GY than SSP (15.4 and 25.8% higher, respectively). No difference between OMF and SSP was observed for RAE-P, despite at the highest P rate had been 21.8% higher with OMF. OMF had a higher RAE-GY than SSP at all P rates which gave to OMF, on average, 25.8% higher RAE-GY. Similar results were observed for RAE-DW except at the lowest P rate (13 kg P ha^{-1}) where SSP was greater than OMF.

Table 3.3 – 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	RAE-SDW		RAE-P		RAE-GY	
		SSP	OMF	SSP	OMF	SSP	OMF
	kg ha^{-1}	------------------------------------ % ------------------------------------					
Maize	17.5	100 a	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	151.62a	100 a	86.67 b
	Mean	100 b	111.35 a	100 b	150.65 a	100	98.24
P source		*		*		ns	
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		*		*		*	

Different letter within row show difference between P source by LSD's test (*P*< 0.05).*, significant at 0.05 error probability.ns, nonsignificant.

3.4 Discussion

3.4.1 Changes in soil phosphorus availability

Soil phytoavailable P (P_{AER}) increased linearly with increasing P rates applied to maize or soybean (Figure 3.6c and 3.6d). There was no difference between OMF and SSP at all P rates, excepted at 52.5 kg P ha^{-1} for maize where 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 (VAN RAIJ et al., 1997), depending on the P rate used. Morais and Gatiboni (2015) also did not find difference between OMF and mineral P fertilizer in a clayey Nitisol. In contrast, Antille, Sakrabani and Godwin (2014) found significantly higher soil extractable P level with SSP compared to a biosolids-derived OMF at two P levels and in two contrasting soils in terms of texture. The OMF did not differ from the control (no P addition). These authors 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 use iron salts.

Although granular OMF produced from poultry litter has been reported to works as a slow-release P fertilizer (SAKURADA et al., 2016), 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 NH_4-P (MAP) whereas SSP, Ca-P. Since NH_4-P has a much higher solubility in water compared to Ca-P, it might have contributed to increase 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 (Figures 3.6e and 3.6f). Consequently, the speed and strength of P adsorption reactions on the surface of soil minerals were similar between OMF and SSP.

3.4.2 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 have a significantly higher relative agronomic effectiveness compared to a reference P fertilizer (SSP), applied to maize or soybean.

Maize and soybean amended with OMF taken up similar amount of P compared to SSP (Figure 3.5). 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. (2015) reported a significant lower SDW yield and lower P uptake by maize when fertilized with an 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 a 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 3.5). 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 larger volume of soil since P has low mobility in soil (FERNÁNDEZ et al., 2009).

By using the difference method (CHIEN et al., 2012) 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 10.9 to 25.74%. The %R by soybean and maize was on average 3.2 and 49.2% higher when fertilized with OMF compared to SSP, respectively. However, it is worth to mentioning that the low %R values observed in this study is result of 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 might be higher.

In a recent study, Sakurada et al. (2016) compared an inorganic NPK fertilizer mix (3-15-2) with two OMF (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 similar grain yield compared to SSP, as shown in Figure 3.4. Similar response was observed for SDW yield. In agreement with our results, Deeks et al. (2013) 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.

We know that maize and soybean are responsive crops to P fertilization in highly weathered soils which have in general, natural low phytoavailable P (SYERS; JOHNSTON; CURTIN, 2008). In this study we also observed response of soybean and maize to P fertilization (Figure 3.4). 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 restrict significantly the crops yield when compared to other studies where higher responses were reported (ALCÂNTARA NETO et al., 2010; OLIVEIRA JUNIOR; PROCHNOW;KLEPKER, 2008; PRADO; FERNANDES;ROQUE, 2001). These results were not expected since the soil available P (P_{AER}) before the experiment was considered low for maize and soybean (Table 3.2), according to recommendations of van Raij et al. (1997).

Nevertheless, leaf P content (Figures 3.6a and 3.6b) in the control was within the sufficiency range (MALAVOLTA; VITTI;OLIVEIRA, 1997) 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 3.2), taking into account its textural class (SOUSA;LOBATO, 2004).

Organic P forms such as phosphomonoesters and phosphodiesters can be a source of P for crops through hydrolysis performed by phosphatases produced by plant roots and soil microorganisms (RICHARDSON et al., 2011). Furthermore, non-phytoavailable P forms is also mobilised by organic anions such as citrate, oxalate and malate released by plant roots (RICHARDSON et al., 2011). A recent study by Carvalhais et al. (2011) reported a significant P mobilisation by organic anions and carbohydrates released by maize roots under low P availability. Similar processes for soybean were described by Wang, Yan and Liao (2010). Thus, these plant and microbial strategies to mobilise 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 (Table3.3). The RAE-DW of OMF increased significantly with P rates. Similarly, Antille, Sakrabani and Godwin (2013) 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 3.5). In soybean, as there was no effect of P sources on P uptake, similar RAE-P between OMF and SSP is expected.

Our results show that the production of OMF from organic wastes like poultry litter in viable alternative to substitute mineral P fertilizers on production of maize and 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. Recent studies have show that about 50% of the P-fertilizer is taken up by maize from the second to fourth successive cropping, however, in greenhouse scale (SAKURADA et al., 2016). Thus, there is a need for long-term field experiments to assess the residual effect of OMFs as well as their potential to mitigates nutrients losses from soil and improve the P fertilization efficiency in highly weathered tropical soils.

3.5 Conclusion

Granular OMF produced from poultry litter not only gives similar crop yields but also has a higher agronomic effectiveness than conventional P fertilizer (SSP), representing a promising P fertilizer for maize and soybean grown in highly weathered soils with low or medium P availability.

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4 FINAL CONSIDERATIONS

Most soils found in tropical regions are very weathered and have low bioavailable P and high P adsorption capacity. In this context, development of new P fertilizers like the granular OMF evaluated here, with similar effectiveness as conventional water-soluble P fertilizers, is relevant, since most P fertilizers used in Brazil are imported. Thus, the use of OMF for crops would help reduce dependence on P mineral resources as well as reduce environmental problems due to inadequate disposal of organic wastes (e.g., poultry litter) in soil, besides its use might fulfil plant-P nutritional requirement.

Although adsorption is the major form of P loss in weathered tropical soils, other forms of losses such as leaching and runoff also occur, especially in sandy and sloppy soils and areas subject to broadcast P application (mineral and/or organic P sources). Even though already well investigated in agricultural systems, these P losses have been ignored by farmers and technicians. Since OMF is a slow release P fertilizer, its use may reduce all form of P loss (adsorption, leaching and runoff), attenuating serious environmental problems like eutrophication of water bodies.