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ORIGINAL PAPER

Use of a Concerning Sewage Sludge in the Manufacture of Organomineral Fertilizers: Agronomical Implications and Sustainable Disposal

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Abstract

Proper sewage sludge (SS) disposal is a concern in tropical regions where there is higher population growth. Use an SS having concerning Zn and Ni contents in the manufacture of organomineral fertilizers (SS-OMFs) to be used in tropical depleted on these nutrients. The effects of SS-OMF rates (40, 60, 80, 100, and 120%, in relation to P_2O_5 and K_2O needs) and physical forms [powder (Pw), granule (G), and pellet (Pt)] on biological (C from microbial biomass, soil basal respiration, and urease activity) and chemical (nutrient uptake and trace elements) indicators of soil quality, as well as on soybean development were evaluated during 60 days in two tropical soils (a clay and a sandy clay loam). Two mineral fertilizations were added [NPK and NPK plus B and Zn (NPK_{B+Zn})]. Results: Organomineral fertilizer rates consistently increased biological indicators of soil quality and soybean vegetative development. Its application rate will depend on the soil texture, i.e., 70% of full P rate was more suitable for the clay soil whereas 100% was for the sandy clay loam. The powder form tended to be more advantageous in terms of supplying P, S, and Zn to soybeans, but N and K may leach. Pelletization could be a workable strategy to avoid it. Organomineral fertilizers based on sewage sludge seem to safely supply Zn and Ni to soybeans even when concerning concentrations are present, but its safety under real application routine remains to be proved. SS-OMF manufacture is a safe strategy for warrantying nutrient and organic matter recycles in tropical regions that are highly dependent on the importation of mineral fertilizers.

Keywords Biosolid · Soil Quality · Nutrient Recycling · Sustainable Management · Tropical Soil

1 Introduction

Sewage sludge (SS) disposal is still a controversial topic even though it can be a source of value-added products, such as fertilizers and soil conditioners (Nascimento et al. 2020; Rodrigues et al. 2021; Rorat et al. 2019). For economic reasons, landfills are its most popular destination (~40%) (Grobelak et al. 2019; Kaza and Yao 2018) despite their high contents of pathogenic microorganisms, toxic organic compounds, and hazardous trace elements (Raheem et al. 2018; Seleiman et al. 2020). However, SS can be used as the organic matrix in the manufacture of organomineral fertilizers (SS-OMFs) which favors its safe disposal in agricultural fields (Antille et al. 2017; Kominko et al. 2019) due to their lower application rates compared to raw SS and to dilution of hazardous substance contents during manufacture (Kominko et al. 2017a; Rodrigues et al. 2021).

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SS-OMFs also turn economically feasible the transportation of the SS to cultivation fields (Seiple et al. 2020). Compared to mineral fertilizers, SS-OMFs often improve sorption or complexation of hazardous trace elements and pesticides, soil aggregation, water flow, nutrient accumulation, and biological indicators of soil quality (Audu and Samuel 2015; Geng et al. 2019; Lynch 2015; Yadav et al. 2018).

South American savanna faces major challenges regarding its agriculture development due to the presence of highly weathered acidic soils with low organic matter and nutrient contents (Gomes et al. 2019), but it is responsible for 52% of soybean *(Glycine max)* production in Brazil (Carneiro and Costa 2016). This is made possible only by the heavy application of mineral fertilizers (MFs), representing ~ 25% of the production costs (Imea 2020). P is the major bottleneck since it is mostly imported (> 50%), phosphate rocks are of low quality in Brazil, and soils have high P-fixation (Pavinato et al. 2020). K is also problematic since it is in high demand, especially by new crop varieties (Bossolani et al. 2018), and it is easily leached in humid regions (Firmano et al. 2020). Finally, Zn, B, and Ni are often amended since Brazilian soils are often depleted in these metals (Rieuwerts 2007).

Annually, Brazil produces ~372,000 dry metric tons of SS (Mateo-Sagasta et al. 2015), which should increase considerably with the introduction of the New Sanitation Legal Framework (Brasil – Federal govenrment 2020). Thus, SS-OMFs may represent a promising strategy for safe disposal of the SS since they often meet most crop nutritional demands and reduce mineral fertilizer importation (Tahat et al. 2020). Adopting SSs having concerning micronutrient contents, especially Zn and Ni, should be even more beneficial due to their soil depletion (Antille et al. 2014; Magela et al. 2019a, b).

This study used an SS with high Zn (2430 mg kg^{-1}) and Ni (298 mg kg^{-1}) contents in the manufacture of OMFs, and evaluated the impact of its rates (40, 60, 80, 100, and 120%; OMF-100% being equal to 100 kg ha^{-1} of P_2O_5 and K_2O) and physical forms [powder (Pw), pellet (Pt), and granule (G)] on soil biological indicators, nutrient accumulations, and soybean development in two typical tropical soils [a clay (CLY) and a sandy clay loam (SCL)]. Two conventional mineral fertilizations [NPK and NPK plus B and Zn (NPK_{B+Zn})] were added as relative controls.

It was hypothesized that (i) use of SS-OMFs would help solve nutritional deficiencies and SS disposal in tropical regions since they improve the biological indicators of soil quality and optimize nutrient uptake and plant development; (ii) Pw should be more efficient than Pt and G in providing nutrients to plants due to its higher contact surface area; (iii) OMF-80% would be enough to supply nutrients in amounts similar to that of mineral fertilization (NPK or NPK_{B+Zn}, supplying 100 kg ha^{-1} of P_2O_5 and K_2O); and (iv) it is safe to use SSs with concerning contents of Zn and Ni to manufacture OMFs on account of the inherent dilution of hazardous substances in their syntheses.

2 Material and Methods

2.1 Attributes of Soils, SS, and SS-OMFs

A clay (CLY, 22°43′30″ S and 47°38′56″ O) and a sandy clay loam (SCL, 21°47′38″ S and 48°10′33″ O) soil, both classified as Typic Hapludoxes, were collected. For each soil, a composed sample (of 10 subsamples) was taken from the upper layer (0–20 cm) of a secondary, semi-deciduous forest, then homogenized, sieved (2 mm), and air-dried. Subsamples were taken to determine soil texture (Bouyoucos 1926), fertility (Raij et al. 2001), and trace element contents (method 3051A; USEPA 2007) (Table S.1). Trace elements were extracted with concentrated nitric acid in microwave oven and quantified by inductively coupled plasma mass spectrometry (ICP-OES).

Sewage sludge (~ 600 kg) was collected from a wastewater treatment plant located at São José do Rio Preto (20°49′12″ S and 49°22′44″ O), São Paulo State/Brazil, having mixed residual sources (domestic and industrial, but mainly domestic). A composted sample (of 5 samples) was taken, homogenized, oven-dried (65 °C) for 48 h, and ground (< 2 mm). Subsamples were taken to determine Escherichia coli (g TS^{-1}) (Part 503 Rule; USEPA 1993), being classified as class A, without pathogenic restrictions (CONAMA 2020). Then, parameters of agronomic interest were determined, such as pH ($CaCl_2$ 0.01 mol L^{-1} and H_2O), moisture, density, and organic carbon (combustion method) (Alcarde, 2009); N-Kjeldahl; P_2O_5 total (acid extraction and colorimetry); P_2O_5 soluble (neutral ammonium citrate plus water); K_2O and Na (acid extraction plus water and flame photometry); Ca, Mg, Cu, Fe, Mn, and Zn (acid extraction and atomic absorption spectroscopy); S-SO_4^{2-} (acid extraction and gravimetry); B (acid extraction and colorimetry), cation exchange capacity (CEC, titration), water-holding capacity (WHC, saturation method) (MAPA 2017); and trace elements (As, Cd, Co, Cr, Cr^{6+}, Hg, Mo, Ni, Pb, and Se) (method 3051A and ICP-OES) (USEPA 2007) (Table S.2). Trace element contents did not exceed threshold values set by the Brazilian normative (CONAMA 2020).

SS-OMF was first synthesized in the powder form (Pw) with the following mass proportions: 67.5% SS; 14.8% monoammonium phosphate (MAP); 13.7% KCl; 0.65% S; 0.35% H_3BO_3; and 3% pre-gelatinized starch to produce the required mix [04-08-08 (NPK) + 0.65% S + 0.035% B + 0.07% Zn]. From Pw, the granulated form (G) was produced by a high-intensity mixer-granulator and the pellet form (Pt) by a 7.5 HP pelletizer (Figure S.1). Nutrient and total trace element contents were determined as for the SS

(Table S.2). SS-OMF met official requirements, except for Ni (IN 61/ 2020).

2.2 Experimental Design and OMF Rates

A greenhouse experiment was conducted in pots, adopting a completely randomized block design with four replicates. The factorial scheme was $[(5 \times 3) + 2]$ that corresponded to five SS-OMF rates (40, 60, 80, 100, and 120%, in which 100% = NPK = NPK_{B+Zn} = 100 kg ha^{-1} of P_2O_5 and K_2O) and three SS-OMF physical forms [powder (Pw), granular (G), and pellet, (Pt)], plus two mineral fertilizations (NPK and NPK_{B+Zn}) as relative controls (Table S.3). Dolomitic limestone was applied to raise soil base saturations to 60% and soils were moistened to 90% of field capacity for 40 days. Then, fertilizers were applied (5-cm depth) and five soybean seeds were sown but trimmed to 2 plants per pot (5L, cultivar 8473 RSF, and 3 cm depth). The seeds were inoculated with peat inoculant (*Bradyrhizobium japonicum*) and treated with a fungicide mixture (carboxin + thiram). The experiment was carried out for 60 days after planting (DAP).

2.3 Biological and Chemical (Trace Elements) Indicators of Soil Quality

After harvesting, soil subsamples were taken to determine urease activity (Tabatabai and Bremner 1972) and C from microbial biomass (C-MB) (Vance et al. 1987). A parallel assay was carried out to assess soil basal respiration (SBR) (Alef and Nannipieri 1995). Trace elements (Cd, Cr, Ni, and Zn) in the soils were determined as described in the item 2.1, but they were below the detection limits (Cd = 0.2 mg kg^{-1}, Cr = 0.5 mg kg^{-1}, Ni = 3.2 mg kg^{-1}, and Zn = 5.4 mg kg^{-1}).

2.4 Nutrient Uptake, Ni Toxicity, and Soybean Development

At 60 days after planting (Figure S.2), shoots were separated from roots (washed in deionized water). Both were oven-dried at 65 °C and their masses recorded. Active nodule numbers were also evaluated (Figure S.3). Shoots were ground (1 mm) and subsamples taken to evaluate both macro (N, P, K, Ca, Mg, and S) and micro (B, Cu, Fe, Mn, and Zn) nutrient contents (Malavolta et al. 1997).

Due to its high content in the SS (298 mg kg^{-1}) (Table S.2), Ni toxicity potential was evaluated under the worst scenarios, i.e., for Pw (due to its higher specific surface area) at higher rates (80, 100, and 120% of the NPK rates) and the soil with lower cation exchange capacity (SCL). Ni contents were determined in both plant parts (shoot and root) and soils (method 3051A, USEPA 2007).

2.5 Statistical Analysis

Data were tested for normality using residual graphs, asymmetry coefficients, kurtosis, and the Shapiro–Wilk test. Next, they were subjected to variance analysis using a generalized linear mixed model (GLM). The Tukey–Kramer' test was applied to the significant interactions. Linear regression was used to explore rate effects on P and K accumulations (Figure S.4). The calculations were performed using SAS (Statistical Analysis System) (SAS Institute Inc., release 9.4, Cary: NC 2014). Finally, Spearman's correlation was used to compare Ni in the roots with urease activity, using PAST software package (Paleontological Statistics) (Hammer et al. 2001). In all tests, a significance level of 5% was adopted.

3 Results

3.1 Biological Soil Quality Indicators

SS-OMF physical forms (Pw, G, and Pt) had no significant impact on the evaluated soil biological indicators, but soil basal respiration (SBR) and C from microbial biomass (C-MB) increased at higher application rates (Fig. 1A, B). SS-OMF60% was enough to generate SBR greater than mineral fertilizers (NPK and NPK_{B+Zn}) in both soils, but SS-OMF rates affected more abruptly C-MB in the SCL (Fig. 1C, D).

3.2 P and K Accumulations in Soybeans

The SS-OMF physical forms did not affect accumulated levels of P and K in soybean tissues, but their rates affected it (Fig. 2). For NPK and NPK_{B+Zn}, P accumulations corresponded to 62–66% and 90–94% of the SS-OMF100% in the CLY and SCL soils, respectively, whereas K accumulations corresponded to about 60% and 94–98% (Figure S.4). In other words, SS-OMF70% for the CLY (Fig. 2A, C) and SS-OMF100% for the SCL (Fig. 2B, D) was enough to supply equal or even higher amounts of P and K to plants than conventional mineral fertilizers, except K in the pelletized form (Pt). The higher contact surface area of the Pw-form seemed to slightly favor P and K uptakes in the CLY soil, but not K in the SCL.

3.3 N, S, B, and Zn Accumulations in Soybeans

SS-OMF physical forms did not consistently affect these nutrients accumulation in the soybean tissues (Table 1). N, S, and B accumulations enhanced with SS-OMF rates (Bindraban et al. 2015), but this was not observed for Zn. Overall, Pt inhibited N-accumulation at lower rates of SS-OMF ($\leq$ 60%) but enhanced it at higher rates ($\geq$ 80%).

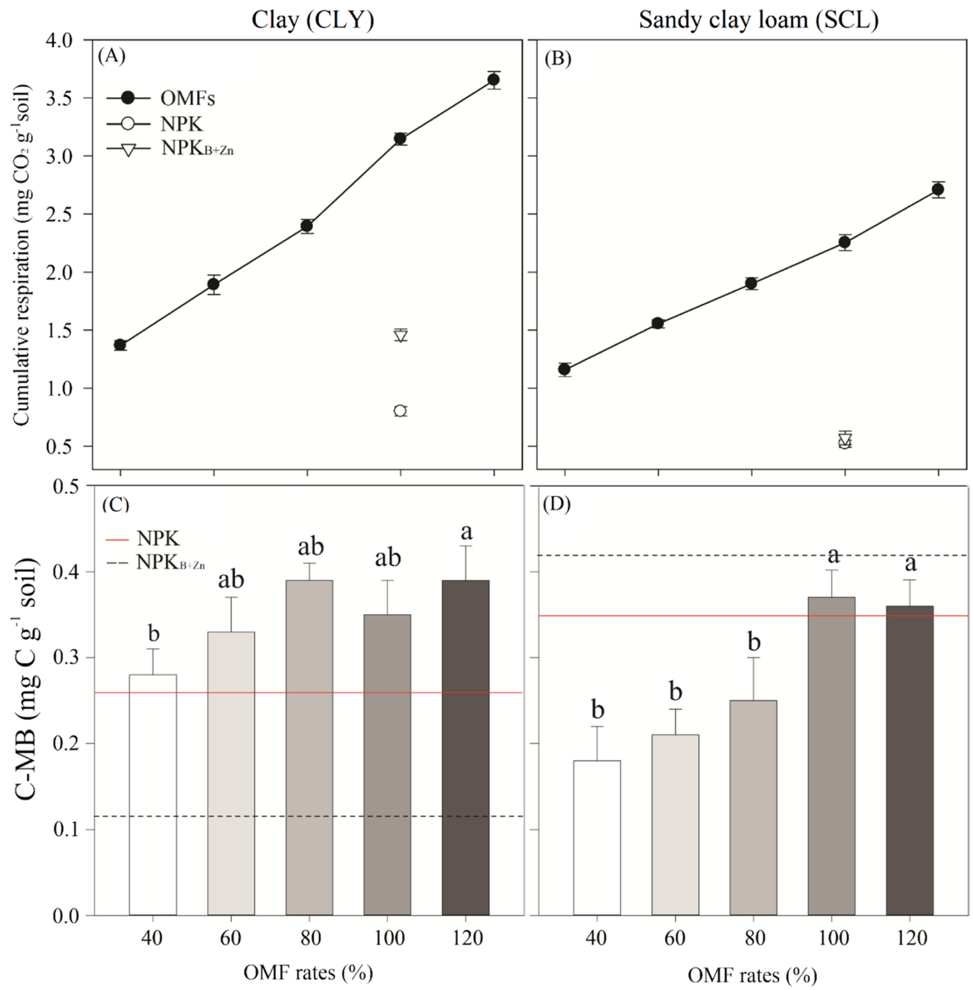

Fig. 1 SS-OMF (organomineral fertilizer from sewage sludge) physical forms (G, Pw, and Pt) and rates (40, 60, 80, 100, and 120%) on soil basal respiration (SBR) (**A**, **B**) and **C** from microbial biomass (C-MB) (**C**, **D**) in two soils (CLY and SCL). Dashed lines represent NPK (mineral treatment), and red lines NPK_{B+Zn} (mineral treatment plus B and Zn). Mean values followed by the same letter(s) did not differ according to Tukey–Kramer's test ($P < 0.05$). Bars indicate mean standard errors ($n = 4$)

NPK and NPK_{B+Zn} accumulated less N than SS-OMFs at any rate (Tables 1 and S.3). Pw seemed to slightly favor S accumulation, mainly in the CLY soil (Table 1). SS-OMF60% and SS-OMF100% for CLY and SCL, respectively, accumulated the same amounts of S as the mineral fertilizations that were subjected to gypsum amendments (Tables 1 and S.4). B accumulation was not affected by SS-OMF physical forms, but enhanced with their rates, especially when ≥ SS-OMF80% (Table 1). At such high B rates (0.4–0.6 kg ha^{-1} of H_3BO_3), soybeans showed slight signs of toxicity (chlorosis evolving to necrosis in mature leaf margins). Obvious signs of toxicity were observed for NPK_{B+Zn}, in which 2 kg ha^{-1} of H_3BO_3 was applied (Table S.3 and Figure S.5). In soybeans, accumulated B contents corresponded to 61–93 mg kg^{-1} for SS-OMFs ≥ 80% and to 133 mg kg^{-1} for NPK_{B+Zn}. Finally, Zn accumulation was not affected by SS-OMF rates, but Pw favored it in the CLY soil (Table 1).

3.4 Ni Accumulation and Urease Activity

Ni contents in the aerial part of soybeans were below the detection limit. However, Pw at rates ≥ 80% accumulated on average 12.8 mg kg^{-1} of Ni in the roots of the SCL, which is much higher than observed for NPK (0.92 mg kg^{-1}) or NPK_{B+Zn} (0.90 mg kg^{-1}). In addition, soil urease activity showed a moderate positive correlation with Ni accumulation in soybean roots ($r = 0.55$, $P < 0.05$). Liming enhanced this soil pH-H_2O from 4.7 to 5.6, but SS-OMF application rates only slightly changed its pH values (to 5.8–6.0) (Table S.5). Therefore, liming impacts Ni hydrolysis and its availability more than amending SS-OMFs.

3.5 Soybean Dry Masses and Root Nodulations

SS-OMF physical forms had no impact, but higher application rates enhanced shoot (SDM) and decreased root (RDM)

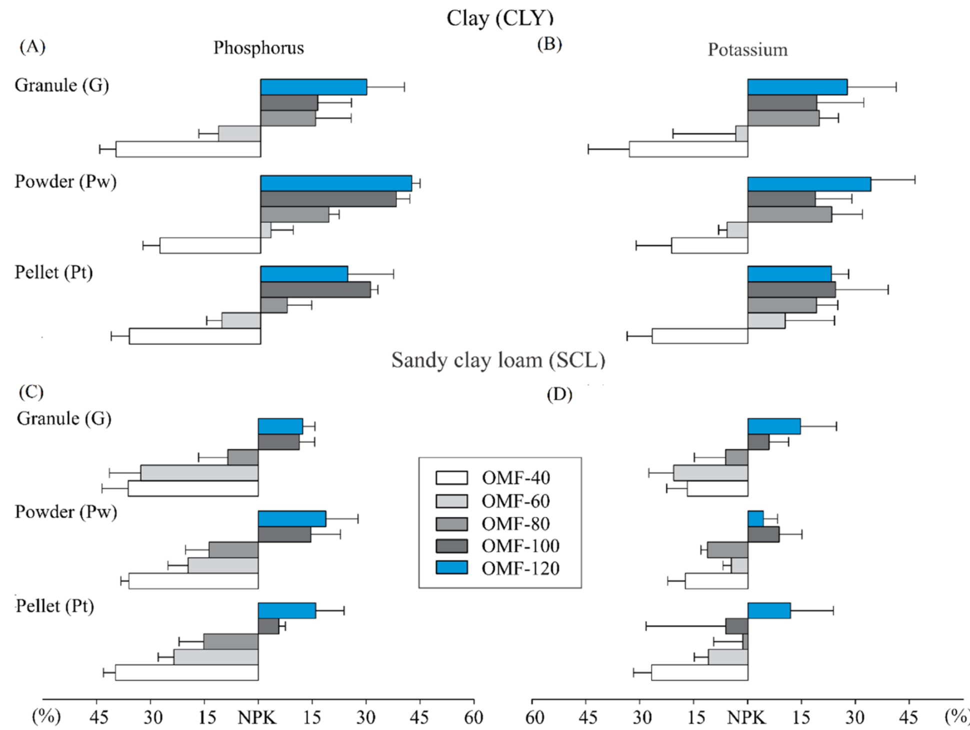

Fig. 2 SS-OMF (organomineral fertilizer from sewage sludge) physical forms (G, Pw, and Pt) and rates (40, 60, 80, 100, and 120%) on the relative amounts of P (**A**, **C**) and K (**B**, **D**) accumulated in soybeans [%, relative to NPK (mineral treatment)] for two soils (CLY and SCL). Bars indicate mean standard errors ($n=4$)

dry masses (Fig. 3). Compared to NPK and NPK_{B+Zn}, SS-OMF60% was enough to increase SDM by 8.2% in CLY, but SS-OMF100% was needed to enhance it by 9.5% in SCL soil (Fig. 3A, B).

Soybean root nodulations clearly decreased with SS-OMF application rates, especially in the SCL (Fig. 4). Nodulation was also affected by soil type, i.e., nodulation was higher in the more nutrient-deprived soil (SCL) (Fig. 4D–F), especially at lower rates. For the SS-OMF treatments, the lack of Co and Mo supplementation did not affect nodulation since the adopted SS contained them (SS-OMF100% has 5.8 and 4.5 g ha^{-1} of Co and Mo, respectively). NPK_{B+Zn} only slightly enhanced nodule numbers.

4 Discussion

Soil microbial activity is highly sensitive to changes in soil management and dictates soil quality and nutrient uptake by plants (Hermans et al. 2020; Horvath et al. 2021). Our results showed that organomineral fertilizers from sewage sludge (SS-OMFs) could be taken up by soil microbes despite their physical forms (powder, granule, or pellet) (Romano et al. 2014). Their organic loads favored soil basal respiration (SBR) in relation to mineral fertilizers, thus suggesting that soil microbes used sewage sludge as a substrate and C-source (Dhanker et al. 2020). Conversely, the high salt contents of the mineral fertilizers contributed to SBR suppression (Shrivastava and Kumar 2015) whereas hazardous substance contents in the SS-OMFs were not enough to inhibit soil microbial activity. Ren et al. (2019) showed that manure amendments enhanced SBR by ~40% when compared to mineral sources, which was less than observed in this study.

Amending SS-OMFs is a simple and promising strategy to supply P and K in tropical regions depleted on these elements, such as those of the Brazilian Savanna. These soils often have high P-fixation due to their high kaolinite and Al and Fe oxyhydroxide (gibbsite and hematite) contents (Carrara Vinha et al. 2021; Hanyabui et al. 2020) as well as low K contents. Soils amended with a poultry litter organomineral fertilizer presented higher contents of P (readily available) than those amended with mineral fertilizers (Frazão et al. 2018), suggesting that the organic fraction (poultry litter) may supply P as well as compete for sorption sites favoring P availability in soils (Campos et al. 2018; Mangalassery et al. 2019; Maranguit et al. 2017). However, soil texture directly impacted the application rate of the SS-OMF for P, as well as for K. The sandy clay loam requested higher rates (SS-OMF100%) than the clay soil (SS-OMF70%).

KCl supplemented ~95% of K in the SS-OMFs, but it is readily available for plants (Kominko et al. 2017b) but also for leaching, especially in soils having low clay and organic matter contents, such as the sandy clay loam (Alfaro et al. 2017; Goulding et al. 2021). Therefore, K requires proper management and constant replenishment due to its mobility in soils (Adesanwo et al. 2013). Pelletization of

Table 1 Total N, S, B, and Zn accumulation in the aerial part of soybean tissues (mg per vessel) as affected by the rates (40, 60, 80, 100, and 120%) and the physical forms (Pw, G and Pt) of a sewage sludge based organomineral fertilizer in two soils (a clay and a sandy clay loam)

Nutrients (mg/vessel)	Physical forms	Organomineral fertilizer rates				
		40%	60%	80%	100%	120%
Clay soil (CLY)						
N	Pw	623 Aa	595 ABa	615 ABa	629 Ba	546 Aa
	G	632 Aa	717 Aa	746 Aa	450 Cb	639 Aa
	Pt	408 Bd	493 Bcd	589 Bbc	774 Aa	685 Aab
S	Pw	31 Ab	39 Aa	39 Aa	39 Aa	40 Aa
	G	28 Ab	31 Bab	36 ABa	32 Bab	33 Bab
	Pt	30 Aa	33 Ba	33 Ba	34 Ba	32 Ba
B	Pw	1452 Ab	1730 Ab	2732 Aa	2767 Aa	3010 Aa
	G	1181 Ac	1700 Abc	2050 Bab	2215 Aab	2758 Aa
	Pt	1340 Ab	2231 Aa	230 ABa	2379 Aa	2535 Aa
Zn	Pw	566 Aa	742 Aa	756 Aa	672 Aa	663 Aa
	G	381 Aa	482 Ba	402 Ba	526 Aa	620 Aa
	Pt	465 Aa	514 Ba	467 Ba	528 Aa	569 Aa
Sandy clay loam soil (SCL)						
N	Pw	422 Aa	484 Aa	410 Aa	516 Aa	408.98 Ba
	G	469 Aa	381 Aa	496 Aa	540 Aa	456.41 Ba
	Pt	386 Ab	397 Ab	550 Aab	640 Aa	654.18 Aa
S	Pw	28 Aa	27 Aab	23 Ab	27 Aab	27 Aab
	G	22 Bbc	21 Bc	25 Aabc	27 Aa	26 Aab
	Pt	22 Bb	22 ABb	26 Aab	27 Aa	26 Aab
B	Pw	926 Ac	1091 Abc	929 Ac	1467 ABab	1596 Aa
	G	935 Ab	972 Ab	1048 Ab	1812 Ab	1606 Ab
	Pt	957 Ab	1010 Ab	1247 Aab	1406 Bab	1546 Aa
Zn	Pw	603 Aa	558 Aa	553 Aa	667 Aa	620 Aa
	G	573 Aa	341 Aa	567 Aa	433 Aa	539 Aa
	Pt	495 Aa	505 Aa	445 Aa	491 Aa	422 Aa

Capital letters show differences between physical forms whereas lowercase letters show differences between rates in the same soil. Mean values followed by the same letter(s) did not differ according to Tukey–Kramer's test ($P \leq 0.05$)

organomineral fertilizers seem to promote nutrients entrapment, decreasing their leaching and favoring their plant uptake, whereas their granulation seem to enhance meso and macropore formation favoring root access to nutrients (Fachini et al. 2021), water retention (Apaeva et al. 2020; Fachini et al. 2021), and microbial growth (Schillem et al. 2019; Šiaudinis et al. 2021). Thus, pelletization of organomineral fertilizers should ensure a slow-release rate for K and increase its plant uptake, mainly in sandier soils (Mazeika et al. 2021).

Mineral fertilization (NPK or NPK_{B+Zn}) contributed to lower N accumulation in soybean tissues than the SS-OMFs, and it would be expected since ~50% of the N applied through mineral fertilizers is lost either through leaching (NO_3^-) or volatilization (NH_3) (Lawrencia et al. 2021). The literature shows that pelletized manure and other organic residues enhanced N-uptake by plants (Johansen et al. 2019; Souri et al. 2019), but our results suggest that it is "rate-dependent." Pellet hardness dictates fertilizer solubilization, and it would limit N-access at lower rates but enhance it at higher rates due to its slower release, thus preventing N-losses (Romano et al. 2014).

SS-OMFs seem to be reliable sources of S and B to plants. Although most S is in non-readily available organic form (~93%), sewage sludge enhances arylsulfatase activity in soils (Godlewska 2018), an S-solubilizing enzyme that hydrolyses sulfate ether into SO_4^{-2} (Acosta-Martinez et al. 2018; Holik et al. 2019). The powder formulation slightly favored S accumulation, mainly in the clay soil. B management requires special attention since its toxicity was observed even at low rates in all OMF physical forms, suggesting that B becomes much more readily available in the presence of organic materials (Dhaliwal et al. 2019; Vera et al. 2021).

Amending soils with sewage sludges rich in Zn and Ni is a very sensitive and controversial issue. In our study, Zn was not supplemented to the organomineral fertilizers, so that the sewage sludge was its unique source, in which Zn is mostly in readily available carbonate and oxide forms (~55–70%)

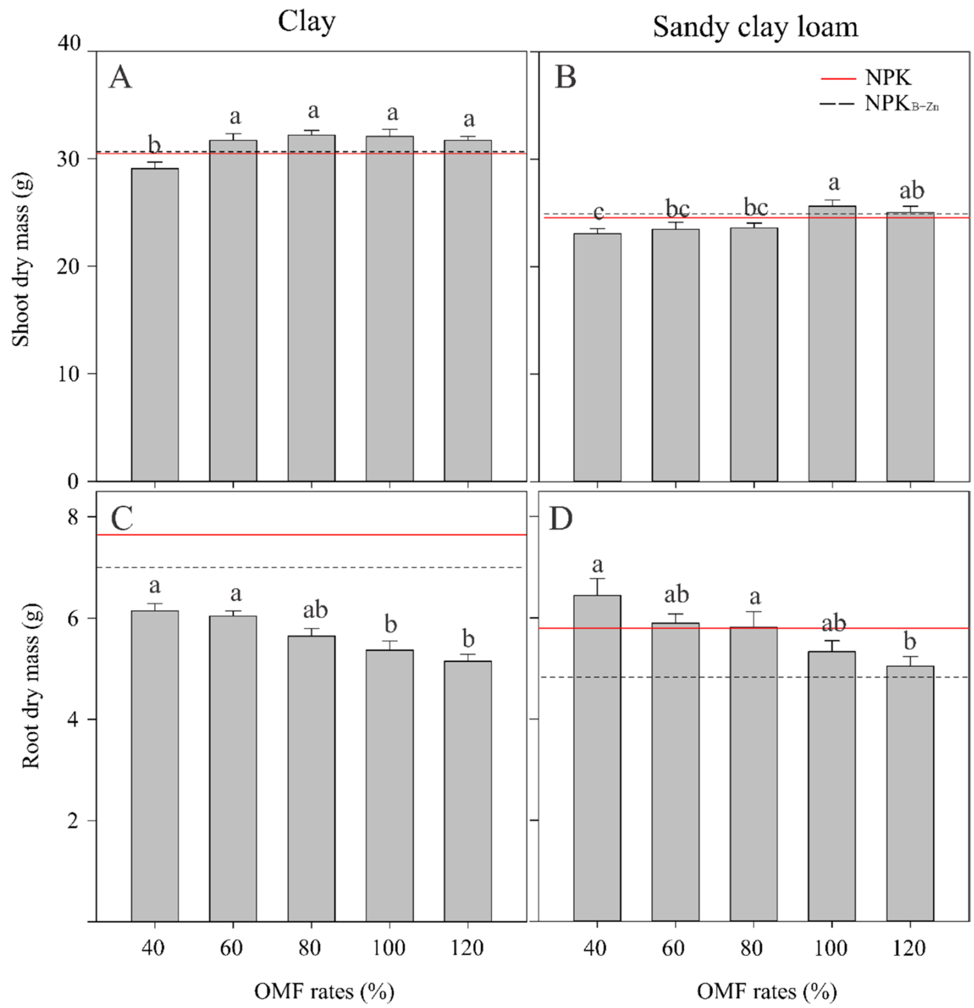

Fig. 3 Vegetative development of soybean plants from SS-OMF (organomineral fertilizer from sewage sludge) rates (40, 60, 80, 100, and 120%) on shoot dry masses (SDMs) (**A**, **B**) and root dry masses (RDMs) (**C**, **D**) for two soils (a clay and a sandy clay loam). Dashed lines represent NPK (mineral treatment) and red lines NPK_{B+Zn} (mineral treatment plus B and Zn); Mean values followed by the same letter did not differ according to Tukey–Kramer's test ($P \leq 0.05$). Bars indicate the mean standard error ($n = 4$)

(Tytła, 2019). Therefore, amending sewage sludge organomineral fertilizers to acidic tropical often enhances Zn availability and soybean yields (Sharma et al. 2016). This element deficiency was worsened by supplying only NPK to these soils for years (Barbosa et al. 2016; Hacisalihoglu 2020), which compromised enzyme and protein syntheses in soybeans (Bagale 2021) and turned plants susceptible to insects (e.g., aphids) and other disease-causing agents (bacteria and fungi) (Helfenstein et al. 2015). Pw favored Zn accumulation in soybeans only in the clay soil, as already pointed in the literature (Galal et al. 2017; Moreno-Lora and Delgado 2020).

Ni contents in the sewage sludge are usually concerning. It ranged from 153 to 179 mg kg^{-1} in the organomineral fertilizers, which is much higher than allowed in Europe (50 mg kg^{-1}) or Brazil (70 mg kg^{-1}). However, Ni contents in the soils (< 9.3 mg kg^{-1}) were much lower than the adopted intervention value in Brazil (190 mg kg^{-1}) (CETESB 2014). Ni is also a plant micronutrient, and its essentiality is related to urease activity, an enzyme that transforms urea and other organic residues into CO_2 and NH_3, thus regulating N metabolism in plants (Yusuf et al. 2011). High Ni contents often reduce both urease activity and plant growth, working as a Ni-stressor indicator in soybeans (Barcelos et al. 2018). Here, N-accumulation in the roots increased with soil urease activity, suggesting that "organic-Ni" enhanced urease activity and N mineralization even when amended at high rates and that Ni toxicity was not reached (Kutman et al. 2013; Silva et al. 2020). Ni availably in soils is highly dependent on soil-pH. Liming the soils increased pH from 4.7 to 5.6, which favors Ni hydrolysis and limits its availability in soils (Magela et al. 2019a, b). Amending SS-OMFs had little effects on soil pH (pH = 5.8–6.0), thus having little effect on Ni availability. Therefore, Ni present in sewage sludge from industrial urban centers might be advantageous and not pose short-term risks for plants and the environment if amended as an organomineral fertilizer to soils with either natural pH > 5.6 or limed to attend this value (Rodrigues et al. 2021). However, long-term studies developed under more realistic field conditions are needed to ratify our findings since Ni accumulated in the roots and may pose risks to the environment.

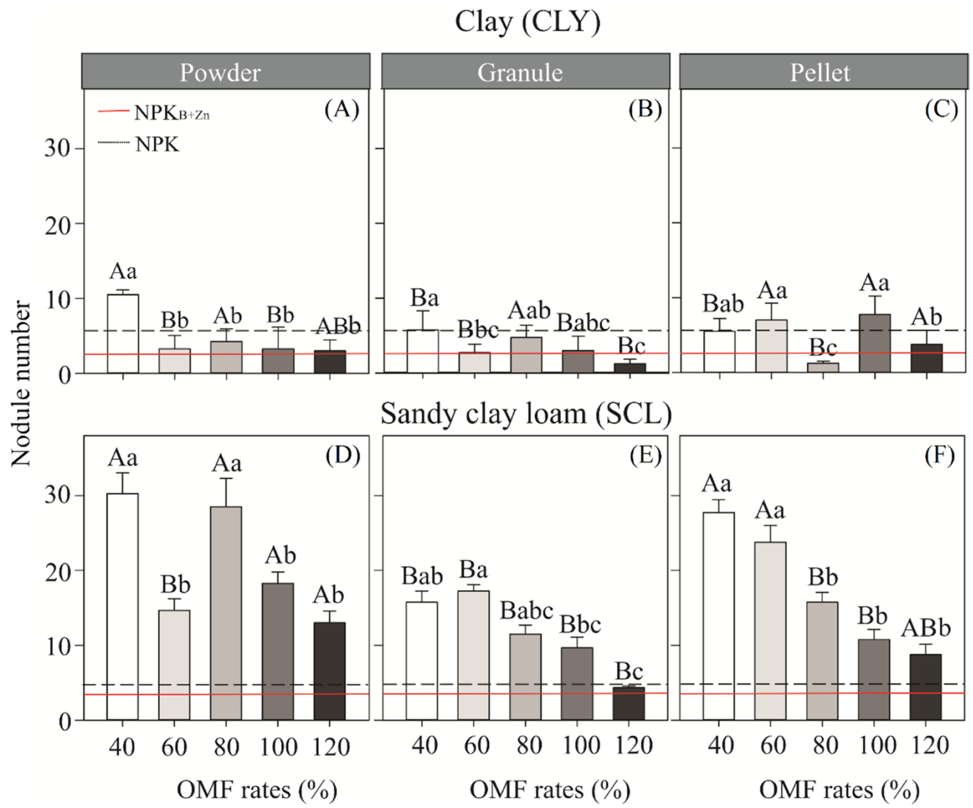

Fig. 4 The effects of SS-OMF (organomineral fertilizer from sewage sludge) rates (40, 60, 80, 100, and 120%) and their physical forms (powder, Pw; granule, G; and pellet, Pt) in soybean nodule numbers in two soils [a clay (**A**, **B**, **C**) and a sandy clay loam (**D**, **E**, **F**)]. Dashed lines represent NPK (mineral treatment) and red lines represent NPK_{B+Zn} (mineral fertilizer plus B and Zn). Capital letters show differences between physical forms whereas lowercase letters show differences between rates in the same soil. Mean values followed by the same letter(s) did not differ according to Tukey–Kramer's test ($P \leq 0.05$). Bars indicate the mean standard errors ($n = 4$)

SS-OMF can promote equal or superior vegetative development for soybeans than mineral sources, depending on soil texture. Higher nutrient loads were needed to increase shoot dry masses in the sandier soil (100% of P needs versus 60% for the clay soil), which has lower buffer capacity and is more deprived of nutrients. A lower rate of a pelletized SS-filter cake OMF (75%) also assured greater soybean vegetative development than the strictly mineral fertilization (Silva et al. 2020).

Soybean roots strategically developed less under a plentiful supply of nutrients, i.e., at higher SS-OMF rates (Fageria and Moreira 2011; Nacry et al. 2013). Plants often change their roots architecture, such as root length, diameter, and angles, when there are P and N deficiencies (Giehl et al. 2014). It might have contributed to higher shoot dry masses when only 40% of the organomineral fertilizer rate was amended to both soil. favored root development, but it did not translate into higher shoot dry masses.

Root nodulation was higher in the sandy clay loam due to its lower natural fertility, but it consistently decreased with organomineral fertilizer application rates. Mineral fertilization also inhibited root nodulation, mainly in the sandy clay loam. Soybeans gave up survival strategies under better nutritional conditions since N-biological fixation is responsible for ~77–99% of N up-taken by soybeans (Lavres et al. 2016). Similar results were reported for other organomineral fertilizers based on sewage sludge in wheat (Antille et al. 2017), sewage sludge plus chicken litter in rapeseed (Kominko et al. 2019), sewage sludge plus filter cake in sugarcane (Gonçalves et al. 2021), and soybeans (Mota et al. 2019). Like Zahoor et al. (2013), the lack of Co and Mo supplementation did not affect soybean nodulation since the adopted sewage sludge contained them.

Sewage sludge organomineral fertilizer benefits go much beyond nutrient inputs (Lori et al. 2017). For example, humic substances resulting from sewage sludge breakdown may act as carriers of genes and enzymes related to nutrient absorption (Nardi et al. 2021) as well as recruit microorganisms capable of promoting plant growth (Lin et al. 2019; Pereira et al. 2021; Wu et al. 2020), thus improving soil quality and plant performance, besides contributing to carbon stocks in soils (Siebielec et al. 2018).

5 Conclusions

Recycling sewage sludge with high Zn and Ni contents into organomineral fertilizers (OMFs) seems a promising strategy for its reuse since it improves biological indicators of soil quality as well as plant nutrition and development, thus avoiding its landfilling. In the short term (60 days), the organomineral fertilizer from sewage sludge physical forms did not consistently have an effect, but their rates did increase the biological indicators of soil quality, nutrient accumulation, root nodulation, and soybean development. In general, 70% of P full rate for the organomineral fertilizer would be recommended for clayer soils whereas 100% would be needed for sandier soils. The powder form seemed slightly more advantageous as a supplier of P, S, and Zn to soybeans, but not N nor K since they may leach. Pelletization might be an appropriate option for preventing their losses, mainly in humid tropical regions, such as the Brazilian Savanna. Sewage sludges are reliable sources of N, P, and S for plants, and it seems that organomineral fertilizers based on them may safely supply Zn and Ni even when they have concerningly high contents. Hazardous substances inherent to the sewage sludge are diluted during manufacturing and are applied at lower rates as organomineral fertilizers, which should prevent or lessen environmental issues. Nevertheless, long-term studies developed under more realistic field conditions evaluating hazardous substances accumulation are still needed to fully validate our findings.

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Declarations

Competing Interests The authors declare no competing interests.

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