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ORIGINAL PAPER

Combining biosolid and mineral sources of phosphorus and potassium in organomineral fertilizers influences the dynamics and efficiency of nutrient release

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Abstract Using urban residues to produce organomineral fertilizers (OMF) is an environmentally friendly strategy that can enhance soil fertility by adding organic matter and mineral nutrients. Herein we investigated the availability of N, P, and K, under organomineral fertilization in sandy soils. An incubation study was conducted using OMF formulated with biosolids as organic matrix and N source, rock phosphate, and potassium sulfate as P and K sources, respectively. Two forms of isolated N, P, and K sources (granulated and non-granulated), five N:P:K granulation proportions (1–2–0, 1–4–0, 1–0–2, 1–2–2, 1–2–4), and a control (unfertilized) were mixed with soil and assessed over a 112 days incubation period. Soil samples were collected at 0, 7, 14, 28, 56, and 112 days to quantify available soil concentrations of ammonium ($N–NH_4^+$), nitrate + nitrite ($N–NO_2^- + N–NO_3^-$), P, and K. The results showed that OMF formulated with NPK had better nitrogen efficiency indexes (NEI) than other formulations and did not induce N immobilization throughout the experiment. Regarding P and K efficiency, OMFs containing phosphorus and potassium increased the indexes compared to the single fertilizer sources. When comparing non-granulated potassium sulfate with granulated, the latter showed a steadier release due to the granulation process. In comparison with rock phosphate at the end of the experiment, the OMFs 1–2–0 and 1–4–2 had higher P available by 116 and 41%, respectively. Based on these results, OMFs have the potential to alter the dynamics of nutrient availability serving as a strategy for nutrient management in agriculture.

Keywords Mineralization · Sustainable nutrient management · Granulation · NPK organomineral fertilizers · Sandy soils · Urban waste management

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Introduction

The term fragile soil is used to define sandy-textured soils with low levels of organic matter and low stability of aggregates or soils with sloping reliefs and susceptible to water erosion (Albuquerque et al., 2015). In Brazil, there are several types of soils with a sandy surface horizon, considered fragile soils, such as the medium texture *Latossolos Vermelhos; Neossolos Flúvicos*, with a sandy-textured A horizon, *Neossolos Quartzarênicos, Argissolos Arênicos* and *Espessarênicos*, and *Planossolos* (Santos et al., 2018) mostly equivalent to Oxisols and Entisols with sandy horizons (NRCS, 2014). In Rio de Janeiro state, especially in the Baixada Fluminense region, the Planossolos class (Soil taxonomy 2014 equivalents: Albaquults, Plintaquults, Albaqualfs, Plintaqualfs with sandy A horizons) occur more frequently. These soils have a sandy surface horizon; therefore, cation exchange capacity (CEC) and, consequently, the availability of nutrients are almost exclusively related to the presence of organic matter. Although sandy soils have low productivity, they have been widely used for agricultural production (Donagemma et al., 2016). Hence, organic matter is critical when managing these soils, as it significantly increases CEC and nutrient retention, mainly nitrogen (N) and potassium (K). As the rates of organic matter losses are higher in sandy soils with agricultural production, it is essential to apply conservation strategies that can promote an increase in the carbon content of these soils and enhance the sustainability of agroecosystems (Albuquerque et al., 2015; Yost & Hartemink, 2019).

Using organic and organomineral fertilizers (OMFs) are a fertility management strategy for fragile soils because it provides greater ecological balance to the system and improves these soils' physical, chemical, and biological properties. Thus, using OMFs produced from organic materials to incorporate nutrients into the production process can favor the cycling of nutrients, as well as promote the improvement of the physical and chemical characteristics of the soil, reducing the dependence on fertilizers inputs and, thus, minimizing environmental impacts (Schultz et al., 2019). OMFs contain in their composition an organic fraction that contributes not only with nutrients but also conditions the soil (e.g., improvements on CEC). This way, the added nutrients remain available to the plants, allowing greater productivity to the system, favoring cycling and increasing the organic matter content of the soil. Moreover, organic fertilizers release nutrients differently from mineral fertilizers because they rely on the decomposition and mineralization of organic waste by soil organisms to make nutrients available which is essential to consider for fertility management strategies (Cruz et al., 2017).

Urban solid waste in Brazil is generally disposed of in sanitary landfills, which, in addition to being costly, contributes to the overloading of landfills in urban areas. However, when treated, stabilized, and properly conditioned, urban residues are then called biosolid as long as it meets the Brazilian Legislation P4.230, of August 1999, of the Environmental Company of the State of São Paulo (CETESB, 1999), which enables its use in agriculture (CONAMA, 2006). According to data from the Brazilian Sanitation Information System (SNIS, 2020), at least around 50% of sewage waste in Brazil has been treated, generating a need to dispose of those residues adequately. Due to their nutrient and organic matter content, biosolids began to be applied in agriculture as soil amendments or as a substrate for seedlings production (Brown et al., 2020; Cabreira et al., 2017; Abreu et al., 2017; Lima-Filho et al., 2019).

The large volume of organic waste (biosolids) generated by sewage treatment is rich in nitrogen, phosphorus (P) and micronutrients, making its use in plant production an alternative to supplying essential elements (Campos et al., 2019; Schlatter et al., 2017). These characteristics indicate the potential of using biosolids in the composition of OMFs, giving a destination to the waste generated by the collection and treatment of sewage sludge that is fundamental for the preservation of the environment and public health. Biosolids also have the potential to reduce CO_2 emissions caused by landfill incineration, diminish chemical fertilizers inputs and increase soil organic matter content (Pereira, 2015).

Furthermore, unlike soluble mineral fertilizers, most of the nutrients in organic and natural fertilizers (rock phosphate and potash) sources are not readily available to plants. In this way, mineralization and nutrient release, in forms available for absorption by plant roots, occur more slowly and are influenced by soil organisms (Ahmed et al., 2019; Basak et al., 2021). Thus, it is essential to know and understand the dynamics of nutrient release by fertilizers in order to achieve a better synchronization for plants' nutritional supply (Cassity-Duffey et al., 2020).

Incubation trials allow the study of the kinetics of nutrients released from fertilizers over time (Cabrera et al., 1994). However, the study of the potential availability of nutrients is mainly carried out for nitrogen, which depends on the mineralization of organic sources for plant uptake (Cabrera et al., 1994; Cassity-Duffey et al., 2020; Eckhardt et al., 2018). In this sense, incubation studies can be an important tool for understanding the dynamics of the release of other macronutrients, such as P and K, by different nutrient sources (Ahmed et al., 2019; Basak et al., 2021; Jalali & Jalali, 2020).

Among several definitions, the term efficiency index (EI) can refer to the ratio between mineralized or available nutrients in the soil and the total amount added through fertilizers (CQFS-RS/S, 2004; Eckhardt et al., 2018). The efficiency index is an efficient parameter to characterize new fertilizers because it can vary depending on the organic waste treatment processes, the fertilizer composition, and the period in which nutrient availability is evaluated. In view of the above, this study developed and characterized OMFs based on biosolid enriched with phosphorus and potassium mineral sources. The hypothesis tested in this work, through incubation studies, is that combining isolated macronutrient sources in OMFs will affect nutrient availability dynamics and efficiency. Moreover, from the results obtained, the objective was to provide a preliminary scientific basis for using these OMFs in agriculture.

Material and methods

Nutrient sources characterization

For the formulation of the OMFs, biosolid supplied by the State Water and Sewerage Company of Rio de Janeiro (CEDAE—Estação Ilha do Governador) was used. Further description of biosolid stabilization and treatment are described in Abreu et al. (2017). The sources of potassium and phosphorus used for the formulation of the compound OMFs were, respectively, potassium sulfate (*Paulifertil Fertilizantes*) and Rock Phosphate (Reactive Natural Phosphate). The components (biosolid, potassium sulfate, and rock phosphate) used in the granulation of the OMFs were characterized in terms of nitrogen and carbon contents, being analyzed by elemental analysis by the CHN method. P and K were determined according to the Manual of Official Analytical Methods for Fertilizers and Amendments (MAPA, 2014). The pseudo-total levels of toxic elements were determined using the USEPA 3050b methodology (USEPA, 1996) (Table 1 of Supplementary Material).

Organomineral fertilizer formulation

The N–P–K granulation proportions (%) were established according to the rates calibrated by Ferrari (2017) and Dias (2018), which have been preset at 1–2–0, 1–4–0, 1–0–2, 1–2–2, 1–2–4, in the following order: biosolid-rock phosphate–potassium sulfate. Biosolids and sources of phosphorus and potassium were classified according to the Brazilian Normative Instruction (IN) No. 25, of July 23, 2009 by the Ministry of Agriculture, Livestock and Supply (MAPA, 2009). Subsequently, the components were macerated in a mortar and then sieved in a 35-mesh sieve to homogenize the three sources at the same particle size.

The granulation of the OMFs was carried out in a pelletizer disk, and 3% of polyvinylpyrrolidone (PVP) additive and washed sand were added to the dry mixture of each formulation to aid the granulation and complete the formula. After the formation of the granules, the fertilizers were classified according to the diameter of the granule. The granules with a diameter between 2 and 4 mm were used in the experiment. Then, the OMF granules were transferred to a forced-air ventilation oven at a temperature of 45 °C for 12 h. At the end of this period, the fertilizers were again classified concerning the diameter of granules, with the 2–4 mm class being considered ideal.

After granulation, the contents of N, P, and K were determined for each OMF formulation, according to the Manual of official analytical methods for mineral, organic, organomineral, and corrective fertilizers (MAPA, 2014), pH was determined in water (1:25), and total organic carbon was determined through wet oxidation due to technical problems with the elemental analyzer used in the preliminary characterization of the sources (Yoemans and Bremner 1988) (Table 1).

Table 1 Chemical characterization of the organomineral fertilizers

Fertilizer	N% (m/m)	P% (m/m)	K% (m/m)	Carbon% (m/m)	*C:N*	pH
BGR	2.1	0.5	0.7	11.7	5.0	4.5
RPGR	0.5	5.2	0.4	1.1	2.0	6.3
PSGR	0.9	0.5	25.9	1.8	1.5	7.2
1–2–0	1.6	0.9	0.7	10.4	6.5	5.5
1–4–0	1.9	1.8	0.8	10.2	5.3	5.0
1–0–2	1.9	0.6	1.4	10.8	5.7	6.0
1–2–2	1.4	1.2	1.6	10.7	6.1	6.2
1–4–2	1.7	2.0	1.3	11.4	6.7	6.3

BGR Granulated biosolid; *PSGR* Granulated potassium sulfate; *RPGR* Granulated rock phosphate

Incubation and efficiency index

After characterization, the fertilizer efficiency index was determined. For that, a soil sample was collected in the 0–15 cm layer of a soil classified as *Planossolo Haplico* (Santos et al., 2018) equivalent to a *Typic fragiaquult* in the Soil Taxonomy classification (NRCS, 2014). The soil had a sandy loam texture and the following chemical characteristics determined according to Teixeira et al. (2017): pH (H_2O): 4.7; H + Al: 2.0 $cmol_c$ dm^{-3}; base saturation: 72%; organic carbon: 2.2 g kg^{-1}; organic carbon: 0.4 g kg^{-1}; P (Mehlich-1): 3.5 mg L^{-1}; K (Mehlich-1): 15.5 mg L^{-1}; Al: 0.4 $cmol_c$ dm^{-3}; Ca: 0.4 $cmol_c$ dm^{-3}; Mg: 0.5 $cmol_c$ dm^{-3}. Dolomitic limestone (0.9 g kg^{-1} equivalent to a dose of 2 Mg ha^{-1}) with PRNT of 80% was added to the soil, which was homogenized, and the moisture was adjusted to 9% (gravimetric moisture) for 20 days prior to the incubation experiment.

To determine the efficiency index of each fertilizer source and fertilizer formulations (OMFs), an incubation experiment was performed in an incubator for biochemical oxygen demand (BOD) for 112 days, evaluating the different proportions of N–P–K of each OMF, according to the methodology adapted from Eckhardt (2015). The experimental design was completely randomized (11 treatments + control) with 4 replications, totaling 48 experimental units. The treatments evaluated were: (1) control (soil, no fertilizer source added); OMFs with the following N–P–K ratios (with biosolid, rock phosphate, and potassium sulfate as sources): (2) 1–2–0; (3) 1–4–0; (4) 1–0–2; (5) 1–2–2; (6) 1–2–4; granulated isolated sources: (7) BGR (granulated biosolid); (8) RPGR (granulated rock phosphate); (9) PSGR (granulated potassium sulfate); and each source isolated, without granulation: (10) biosolid; (11) rock phosphate; and (12) potassium sulfate, in order to observe the behavior of granulation in the availability of nutrients. The rate of OMF, BGR, and biosolid added in each container was 1.6 g per container (equivalent to the addition of 80 kg N ha^{-1}), equivalent to the recommendation for maize in the Fertilization and Liming Manual for Rio de Janeiro (Freire et al., 2013). For sources without N, 0.23 g of rock phosphate and RPGR and 0.05 g of potassium sulfate and PSGR per container were added (equivalent to the lowest rates of P and K present in the treatments with NPK due to OMF application).

The incubation study was performed in glass containers of 120 mL, which comprised the experimental units. Each container received 134 g of soil with 9% gravimetric moisture (equivalent to 123.3 g of dry soil at 105 °C). In the first stage, 68.5 g of moist soil and half the amount of fertilizers for each treatment were added. The material was homogenized and compacted up to 2.5 cm of the containers. In the second stage, the remaining soil and each fertilizer were added, homogenizing and compacting them to a height of 5 cm, thus reaching a density of 1.2 g cm^{-3}, equivalent to the density of *Planosolos*. Four replicates of each treatment were randomly placed in 12 glass pots with a capacity of 2.0 L, which were placed in an incubator chamber in the absence of light and controlled temperature conditions (25 ± 1℃). The pots were opened weekly for 10 min to avoid O_2 deficiency, at which time soil moisture was monitored by weighing the experimental units.

The evaluation of N mineralization, as well as the availability of P and K from the organic fertilizers, were performed at the time of installation of the incubation experiment (time 0) and at 7, 14, 28, 56, and 112 days after the start of incubation.

Available concentrations of ammonium ($N–NH_4^+$), nitrate + nitrite ($N–NO_2^- + N–NO_3^-$), P, and K (Mehlich-1) were determined as described in Tedesco et al. (1995). Results were expressed in mg kg^{-1} dry soil. Soil inorganic N (N_{ino}) was obtained with $N–NH_4^+$ and $N–NO_2^- + N–NO_3^-$ values (Eq. 1):

$$N_{ino} = N - NH_4^+ + N - NO_2^- + N - NO_3^- \tag{1}$$

The N mineralization or immobilization processes from organic fertilizers in the soil throughout the incubation period were evaluated through the net mineralization of N (N_{net}) (Eq. 2):

$$N_{net} = N_{ino}\text{soil with fertilizer} - N_{ino}\text{control} \tag{2}$$

where, N_{net} indicates whether there was a predominance of N mineralization (positive value) or N immobilization (negative value) at each sampling time and for each soil/fertilizer combination (Eckhardt, 2015).

The availability or immobilization of P and K from organic fertilizers in the soil was evaluated through the net availability of P (P_{net}) and K (K_{net}) (Eqs. 3 and 4, respectively):

$$P_{net} = P_{available}\text{soil with fertilizer} - P_{available}\text{control} \tag{3}$$

$$K_{net} = K_{available}\text{soil with fertilizer} - K_{available}\text{control} \tag{4}$$

The Efficiency Index of organic fertilizers (Eqs. 5, 6, and 7) was calculated from the rate of total rates added of N, P, and K (N_{tot}, P_{tot} e K_{tot}, respectively) and the available amount of N, P, and K present in the soil after each treatment incubation period:

$$NEI = \left(N_{net}/N_{tot}\right) \tag{5}$$

$$PEI = \left(P_{net}/P_{tot}\right) \tag{6}$$

$$KEI = \left(K_{net}/K_{tot}\right) \tag{7}$$

where: EI = efficiency index; tot = amount added via fertilizer + soil content, determined, according to Tedesco et al.(1995) in mg kg^{-1}; net = content available at each time evaluated in mg N kg^{-1}.

Statistical analysis

Statistical analysis of the experimental data was performed using R software. The generalized least squares model was the one that best fitted the experimental data, where fertilizer treatments were incorporated as the within-group heteroscedasticity structure to account for unequal variance (*varIdent*, *nlme*) (Pinheiro & Bates, 2022). This approach was utilized since some treatments did not comprise a macronutrient in their composition and consequently homogeneity of the variances was not expected a priori. The parameters (mineralized N, available P, and K, NEI, PEI, KEI) were evaluated as a function of treatments and time. Posteriorly, the data analysis of variance was performed, which indicated a significantly different interaction for each parameter analyzed with time (*P*-value < 0.0001), except for NEI with time (*P*-value = 0.178). A post hoc multiple comparison test was performed using Sidak's adjustment with a confidence level of 95% (*emmeans*, *multcomp*) (Bretz et al., 2021; Hothorn et al., 2008; Lenth et al., 2022; Piepho, 2004).

Results and discussion

Characterization of the sources used in the formulation and the OMFs

The P content obtained in rock phosphate and K in potassium sulfate was 22.4 ± 1.2% and 45.6 ± 1.5%, respectively. In the biosolid, the N content is within what is usually found in sewage treatment residues, which generally varies between 0.5 and 2% (Ahmed et al., 2010), being similar to the results found for biosolids originating from the same treatment plant (ETE Ilha—CEDAE RJ) used in this work, that had values between 1.5 and 3.0% over different years (Abreu et al., 2017; Cabreira et al., 2017). It is important to highlight that the biosolid composition is variable (Nascimento et al., 2020), as the input of household waste also varies over time.

The levels of iron (Fe), chromium (Cr), and cadmium (Cd) are higher in Rock Phosphate than in other sources. However, only chromium and cadmium have regulatory limits in mineral phosphate fertilizers according to the Brazilian Normative Instruction no. 7, of May 2, 2016, from the Ministry of Agriculture, Livestock and Supply (MAPA, 2016), which were below the maximum allowable limit (40 mg kg^{-1} to Cr e 4 mg kg^{-1} to Cd) in this study. The values of nickel, copper, chromium, zinc, lead, and cadmium in biosolids (maximum values allowed 50, 1500, 1000, 300, and 39 mg kg^{-1}, respectively) are also below the maximum limit established by Resolution 375 of August 29, 2006, from the Brazilian National Council for the Environment (CONAMA, 2006), which regulates sewage sludge quality requirements for agricultural application.

The chemical characterization of the organic fertilizers used in the incubation is described in Table 1. The proportion of nutrients is in accordance with the values determined for formulating organominerals. The biosolid and the BGR granulated fertilizer (biosolid under granulation) had the lowest pH values. Rock phosphate (granulated and non-granulated), as well as OMFs with sources of K in the composition (1–0–2, 1–2–2, and 1–4–2), showed more acidic pH, while those of source of K, a pH close to neutrality, which is not desirable since the addition of fertilizers with a pH close to or above 7.0 favors the loss of N–NH_4^+ by volatilization.

Fertilizers containing N had a similar total carbon (C) and *C/N* ratio. The *C/N* ratio is one of the most used parameters to indicate the stabilization of organic fertilizers, considered ideal when it is between 20 and 25. Residues with a *C/N* ratio below 10 can result in excessive nitrogen loss through ammoniacal forms, as they promote rapid mineralization of organic matter. Furthermore, adding low *C/N* residues to agricultural systems may not facilitate carbon accumulation because the added nitrogen substrate will favor carbon mineralization instead (Brust, 2019). The values of the *C/N* ratio for all OMFs studied were below 10, consistent with the *C/N* ratio of activated sludge (Kiehl, 2010). Nevertheless, the advantage of low *C/N* residues lies in their rapid mineralization, which enhances nutrient availability for crops being a desired characteristic of the OMFs used in the present study as the unique N source. Moreover, Lavallee et al. (2020) highlight that the stabilization of the organic matter relies more in the physical properties of the organic residue rather than its chemical composition indicating that even the addition of a low C/N residue could still enhance soil organic matter.

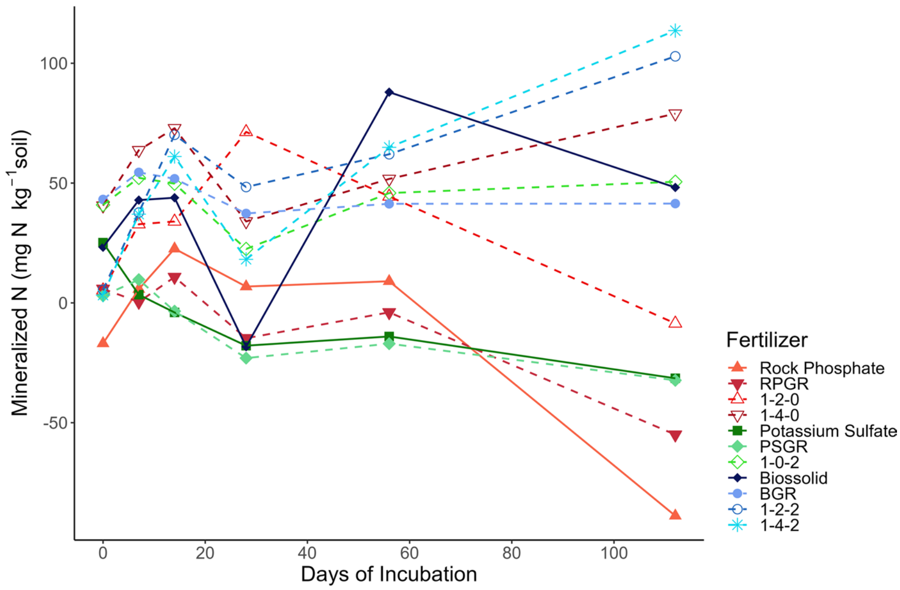
Nitrogen mineralization

The efficiency index (EI) of organic fertilizers is an important aspect of organic fertilizers as it represents the ratio of nutrients solubilized or mineralized to the total amount of nutrients added to the soil through the organic source. The Nitrogen Efficiency Indexes (NEI) obtained in this study are fully in accord with the method´s base literature (CQFS-RS, 2004), which determines an NEI of 0.20 for materials in the class of sewage sludge and waste compost. The fertilizers that showed a reduction in net N in the initial phase of the study were those that did not have N in their composition. The mean NEI obtained in all OMFs over the 112 days of incubation were higher than 0.21. Similar behavior was observed in a study with organic waste (Ansong Omari et al., 2018), in which the highest values of N were observed at 120 days of incubation.

The average NEI found (>0.21) in the OMFs was similar to that found herein for the granulated biosolid (0.25) and higher than that found for the biosolid without granulation (0.19). This average NEI, both in OMFs and in granulated biosolid, was higher when compared to data obtained in other studies. Higher NEI found in the OMF suggest that these fertilizers are more efficient in providing N than other organic sources. For example, Eckhardt et al. (2018) found NEI between 0.10 and 0.20 in 112 days when studying composted and non-composted dairy manure, whereas Oliveira et al. (2012) found a negative NEI value (immobilization indicative) for sewage residues when studying N mineralization of 15 organic compounds in a short period of field observations (28 days). The difference in NEI among the results obtained herein and by Oliveira et al. (2012) can be justified by the composition of sewage residues (biosolids) being variable depending on their origin and also due to the stabilization phase in residue treatment, which can result in an organic residue with higher C:N.

In general, OMFs showed a reduction in net mineralized N from 14 to 56 days (Fig. 1). In contrast, when studying different categories of fertilizers, Cassidy-Deffey et al. (2020) observed an increase in N mineralization between the period of 14–56 days in organic compounds. However, the greatest N release by organic compounds also occurred between 40 and 60 days, with mineralization of 15–35% of the

Fig. 1 Net nitrogen mineralization versus soil incubation time. Values are the average of four replicates, which according to ANOVA are significantly different with incubation time. Mean comparison data between treatments across days are displayed as supplementary material to avoid cluttering the plots. *BGR* Granulated biosolid; *PSGR* Granulated potassium sulfate; *RPGR* Granulated rock phosphate



applied N (equivalent to an NEI of 0.15–0.35) similar to that observed in the present study.

Throughout the evaluation period, OMFs 1–2–2 and 1–4–2 showed the highest net N mineralization among the evaluated fertilizers, with an average value of 56 and 67 mg N kg^{-1} of soil, respectively (Fig. 1). These formulations showed average NEI of 0.30 and 0.25, respectively, and did not show N immobilization until 112 days of incubation (Table 2), which is expected for stabilized organic compounds (Cassity-Duffey et al., 2020). The absence of immobilization during this period is an important factor, as the lack of N in the soil can limit the development of crops, as evidenced by Eckhardt et al. (2018). The OMFs 1–2–2 and 1–4–2 have all nutrients (NPK) in their composition, highlighting the possible influence of P and K as stimulators of nitrogen mineralization, especially because N is well stabilized in the biosolid (sludge stabilization process).

Phosphorus solubilization

The highest amounts of solubilized P (Fig. 2) were observed in phosphate sources (granulated and non-granulated P sources) and in OMFs with P in their composition. However, P solubilized at 28 days onwards was higher in OMFs 1–2–0 and 1–4–2 (> 130 mg P kg^{-1}) compared to isolated sources, RPGR (86 mg P kg^{-1}) and rock phosphate (63 mg P kg^{-1}). At 112 days, P solubilized from 1–2–0 was 116% higher than rock phosphate and 1–4–2 was 41%. Ahmed et al. (2019) also reported this increase in P solubilization when comparing the application of rock phosphate mixed with manure to the application of Rock phosphate alone in an incubation study. Greater P availability obtained with the OMFs can be given, either by adding P through the biosolid or by the indirect benefits of the organic fraction. The organic fraction protects the mineral fraction and reduces the contact surface of P with the active sites for immobilization, minimizing the potential for P fixation in the soil (Borges et al., 2019; Corrêa et al., 2018).

The slow release of nutrients in natural phosphate rocks can be confirmed by the initial Phosphorus Efficiency Index (PEI) (Table 1) of OMFs 1–2–2 and 1–2–4, which showed negative PEIs in the first days of incubation. An immobilization process occurred, that is, this treatment presented lower values than the control. The P available in the soil was immobilized before it started to be released by the added fertilizers, which occurs after 28 days of incubation. According to Ranno et al. (2007), P is transferred from the soil solution to the solid phase after adding phosphorus to the soil. Part of this element is specifically adsorbed to iron and aluminum oxides, therefore becoming unavailable to crops. With OMFs, the transfer of P to the solution becomes slower due to granulation

Table 2 Efficiency Index of nitrogen, phosphorus and potassium of organomineral fertilizers and sources (granulated and non-granulated)

Days	0			7			14			28			56			112		
Treatment	EM	CI_{low}	CI_{up}	EM	CI_{low}	CI_{up}	EM	CI_{low}	CI_{up}	EM	CI_{low}	CI_{up}	EM	CI_{low}	CI_{up}	EM	CI_{low}	CI_{up}
Nitrogen efficiency index																		
1–0–2	0.20	0.07	0.33	0.37	0.24	0.50	0.41	0.28	0.54	0.22	0.09	0.35	0.27	0.14	0.39	0.34	0.21	0.47
1–2–0	0.17	−0.07	0.42	0.33	0.08	0.57	0.30	0.05	0.54	−0.06	−0.31	0.18	0.11	−0.13	0.35	0.36	0.12	0.60
1–4–0	0.13	−0.04	0.30	0.25	0.07	0.42	0.22	0.04	0.39	0.32	0.14	0.49	0.28	0.11	0.45	0.16	−0.01	0.34
1–2–2	0.07	−0.06	0.20	0.37	0.24	0.50	0.36	0.23	0.49	0.29	0.16	0.43	0.30	0.17	0.43	0.38	0.25	0.51
1–2–4	0.03	−0.07	0.14	0.28	0.18	0.39	0.36	0.26	0.46	0.18	0.08	0.29	0.28	0.17	0.38	0.39	0.28	0.49
Biosolid	0.03	−0.14	0.21	0.27	0.10	0.45	0.27	0.10	0.45	−0.10	−0.28	0.07	0.34	0.17	0.52	0.33	0.15	0.50
BGR	0.26	0.11	0.41	0.31	0.16	0.46	0.27	0.12	0.42	0.17	0.02	0.32	0.21	0.06	0.36	0.28	0.13	0.43
P. Sulfate	−0.02	−0.35	0.31	0.10	−0.23	0.43	−0.29	−0.62	0.04	−0.02	−0.35	0.31	−0.32	−0.65	0.01	0.12	−0.21	0.45
PSGR	0.06	−0.25	0.37	0.03	−0.28	0.34	−0.06	−0.37	0.24	−0.39	−0.69	−0.08	−0.10	−0.41	0.21	0.16	−0.14	0.47
Rock P	−0.07	−0.42	0.28	0.17	−0.18	0.52	0.03	−0.32	0.38	0.01	−0.34	0.36	0.01	−0.34	0.36	0.03	−0.32	0.38
RPGR	0.08	−0.26	0.43	−0.11	−0.46	0.24	0.15	−0.20	0.50	0.06	−0.29	0.41	0.08	−0.27	0.42	0.07	−0.28	0.41
Phosphorus efficiency index																		
1–0–2	0.39	0.06	0.73	0.06	−0.27	0.39	0.94	0.61	1.27	0.66	0.33	0.99	0.80	0.46	1.13	0.94	0.61	1.27
1–2–0	0.55	−0.01	1.12	0.95	0.39	1.52	1.00	0.43	1.57	0.93	0.36	1.49	0.97	0.40	1.54	0.58	0.01	1.15
1–4–0	0.15	−0.99	1.30	0.19	−0.95	1.34	1.30	0.16	2.45	0.99	−0.16	2.13	0.99	−0.15	2.14	1.00	−0.14	2.14
1–2–2	−6.74	−11.86	−1.62	−0.59	−5.71	4.53	0.54	−4.58	5.66	0.93	−4.19	6.05	0.89	−4.23	6.01	0.98	−4.14	6.10
1–2–4	−0.68	−2.14	0.78	−1.00	−2.46	0.46	0.48	−0.98	1.94	0.99	−0.47	2.45	0.99	−0.47	2.45	1.00	−0.46	2.46
Biosolid	0.67	−0.15	1.48	0.76	−0.06	1.58	0.93	0.11	1.74	0.97	0.15	1.78	0.98	0.16	1.80	0.29	−0.52	1.11
BGR	0.69	−0.62	2.00	−0.28	−1.59	1.03	0.94	−0.37	2.24	0.72	−0.59	2.03	0.54	−0.77	1.85	0.89	−0.42	2.20
P. Sulfate	0.06	−5.16	5.28	−0.33	−5.55	4.89	0.79	−4.43	6.01	0.91	−4.32	6.13	−5.26	−10.48	−0.04	0.33	−4.89	5.55
PSGR	0.40	−3.36	4.15	0.23	−3.53	3.98	0.70	−3.06	4.45	0.17	−3.59	3.92	2.85	−0.91	6.60	0.25	−3.50	4.01
Rock P	0.95	0.93	0.96	0.96	0.94	0.97	1.00	0.99	1.02	0.94	0.92	0.95	0.99	0.98	1.01	0.99	0.98	1.01
RPGR	0.53	−0.28	1.34	1.58	0.77	2.39	0.98	0.17	1.79	0.95	0.14	1.76	0.98	0.17	1.79	0.97	0.16	1.78
Potassium efficiency Index																		
1–0–2	0.47	0.27	0.67	0.66	0.46	0.86	0.76	0.56	0.96	0.74	0.54	0.94	0.79	0.59	0.99	0.59	0.39	0.79
1–2–0	0.22	0.00	0.45	0.07	−0.16	0.30	0.03	−0.20	0.26	−0.37	−0.59	−0.14	−0.03	−0.25	0.20	−0.57	−0.80	−0.35
1–4–0	0.26	−0.02	0.53	0.07	−0.20	0.35	0.05	−0.22	0.33	−0.17	−0.45	0.11	0.10	−0.18	0.37	−0.30	−0.58	−0.02
1–2–2	0.18	0.04	0.33	0.53	0.38	0.67	0.68	0.54	0.83	0.72	0.57	0.86	0.85	0.70	1.00	0.57	0.42	0.71
1–2–4	0.15	−0.07	0.38	0.50	0.27	0.72	0.71	0.49	0.93	0.78	0.55	1.00	0.87	0.64	1.09	0.53	0.31	0.76
Biosolid	0.00	−0.12	0.13	−0.01	−0.14	0.11	−0.07	−0.19	0.06	−0.44	−0.56	−0.31	−0.04	−0.16	0.09	0.23	0.11	0.36
BGR	0.09	−0.25	0.43	0.06	−0.28	0.39	−0.05	−0.39	0.29	−0.13	−0.46	0.21	0.05	−0.29	0.39	−0.59	−0.93	−0.25

Table 2 (continued)

Days	0			7			14			28			56			112		
Treatment	EM	CI_{low}	CI_{up}	EM	CI_{low}	CI_{up}	EM	CI_{low}	CI_{up}	EM	CI_{low}	CI_{up}	EM	CI_{low}	CI_{up}	EM	CI_{low}	CI_{up}
P. Sulfate	0.71	0.67	0.75	0.71	0.67	0.74	0.76	0.72	0.80	0.74	0.70	0.78	0.81	0.77	0.85	0.85	0.82	0.89
PSGR	−0.14	−0.27	−0.01	0.45	0.32	0.58	0.69	0.56	0.82	0.78	0.65	0.91	0.81	0.69	0.94	0.61	0.48	0.74
Rock P	0.07	−0.14	0.29	0.07	−0.15	0.28	−0.11	−0.32	0.11	−0.28	−0.50	−0.07	0.01	−0.21	0.22	0.06	−0.16	0.27
RPGR	0.23	−0.01	0.47	0.02	−0.22	0.26	−0.09	−0.33	0.16	−0.17	−0.42	0.07	0.00	−0.24	0.25	−0.74	−0.99	−0.50

EM estimated mean; CI_{low} lower confidence interval; CI_{up} upper confidence interval. *BGR* Granulated biosolid; *P. Sulfate* Potassium sulfate, *PSGR* Granulated potassium sulfate; *Rock P* Rock Phosphate, *RPGR* Granulated rock phosphate. Means in the same date, which confidence intervals overlap are not statistically different (Sidak's adjustment, $P < 0.05$)

(Frazão et al., 2019) which favors an initial immobilization. However, the organic fraction contributes to the increase in soil CEC, that could be potentially disfavoring P fixation later in the incubation experiment. Mumbach et al. (2019) observed similar behavior in a field trial, in which the use of OMF influenced a more controlled release of P to the soil solution.

The biosolid (not granulated) and BGR (granulated), even without the addition of P sources in their composition, showed similar behavior regarding the dynamics of P solubilization but resulted in lower available P contents, which is consistent with the amount of P in its composition (Table 1). Jalali and Jalali (2020) also found different dynamics of P release when evaluating various organic and inorganic fertilizers. These results suggest that the dynamics of P availability over time is variable for different fertilizers, regardless of the source, and should be considered in nutrient management, especially when applying alternative fertilizer sources.

The OMFS 1–2–2 and 1–2–4 showed PEI > 0.60 from the 28th day onwards despite presenting P immobilization in the first 7 days (Fig. 2). These values are higher than those of Eckhardt et al. (2018), who found PEI > 0.53 from the 28th day onwards for fertilizers obtained from vermicomposted bovine manure. The difference between these studies is mainly related to the manure composition, where PEI is lower (Eckhardt et al., 2018) because the P concentration found in the manure is the only contribution of P through mineralization, while in the present study, a mineral phosphate source was added to increase the biosolid's PEI when formulating the OMF.

Potassium solubilization

The highest amounts of K solubilized (Fig. 3) were observed in potassium sulfate (non-granulated), PSGR (granulated), and in OMFs with K in their composition (1–2–2 and 1–4–2). Some treatments showed a negative potassium efficiency index (EIK), indicating immobilization of the nutrient, especially in fertilizers without K in their formulation (Table 2). However, at time 0, the EIK of sample PSGR (potassium sulfate granulated) also showed a negative value, which may indicate that the granulation promotes a more controlled release of the nutrient since non-granulated potassium sulfate has high solubility

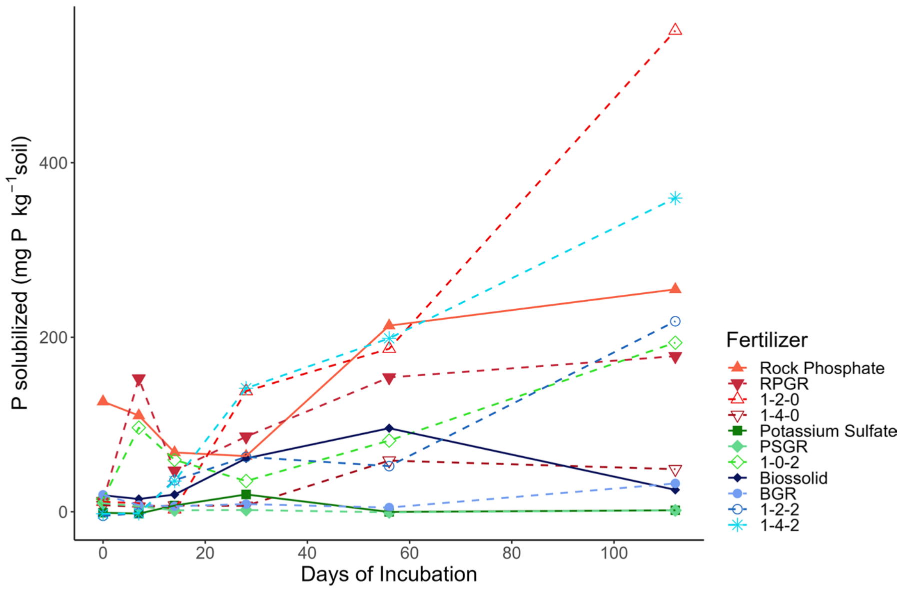


Fig. 2 Net phosphorus solubilization versus soil incubation time. Values are the average of four replicates, which according to ANOVA are significantly different with incubation time. Mean comparison data between treatments across days are displayed as supplementary material to avoid cluttering the plots. *BGR* Granulated biosolid; *PSGR* Granulated potassium sulfate; *RPGR* Granulated rock phosphate

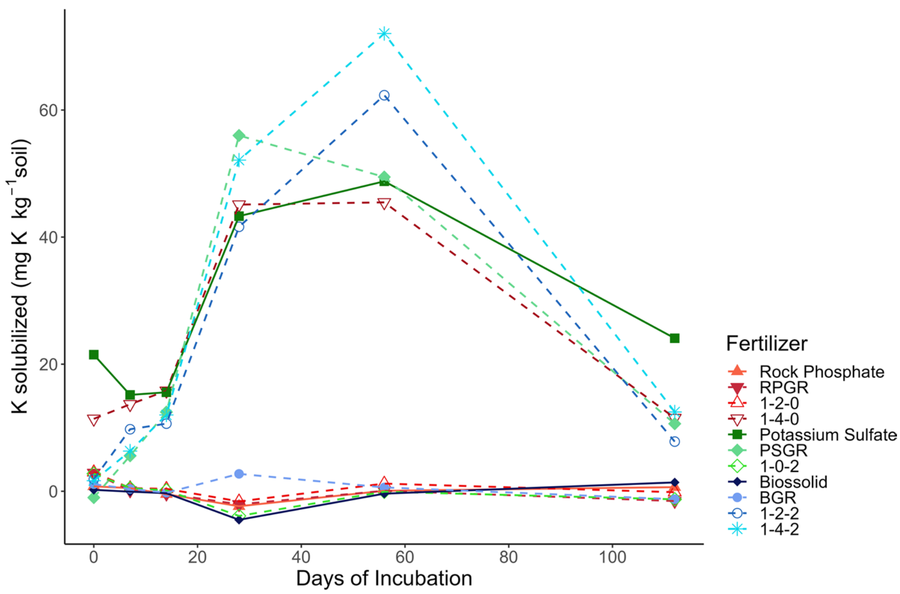


Fig. 3 Net potassium solubilization versus soil incubation time. Values are the average of four replicates, which according to ANOVA are significantly different with incubation time. Mean comparison data between treatments across days are displayed as supplementary material to avoid cluttering the plots. *BGR* Granulated biosolid; *PSGR* Granulated potassium sulfate; *RPGR* Granulated rock phosphate

and considerable concentration of K. The granulation affects the contact surface of the fertilizer with the soil and, consequently, the solubilization of K to the soil solution. Similar behavior of nutrient solubilization when using rock powder was observed by Basak et al. (2020) with a greater release of K in treatments with smaller granulometry which, as opposed to granulation, increases the contact surface between the fertilizer and the soil, resulting in faster solubilization of the nutrient.

Fertilizers 1–0–2, 1–2–2, and 1–4–2 showed higher KEI, especially from 14 to 56 days, when K requirements of mostly vegetable crops are higher (Freire et al., 2013). Biosolids generally have a low K content since it is a mobile nutrient that is lost during stabilization process of sewage sludge conversion to biosolid, in which most of the moisture is removed

(Abreu et al., 2017). Adding a K source allows greater efficiency of K fertilization when added to the organic source. In turn, the biosolid as an organic source can potentially reduce nutrient losses, which is more significant in sandy soils because they are well-drained with low CEC.

Agricultural application

In this study, the determination of the potential mineralization/availability of nutrients is estimated without the cultivation of plants and under ideal conditions of temperature and humidity. Hence, the availability of nutrients tends to be different under field conditions. The solely consideration of this index for crops, or even fertilizers, can result in fertilization below the crop's needs, providing nutrients in insufficient amounts for plant nutrition. Nevertheless, these results are fundamental to understanding nutrient availability dynamics and can guide future studies with different organic and mineral sources regarding the efficiency of inputs for agriculture. The discussion in this work indicates that different macronutrients (NPK) can influence nutrient mineralization and suggest that granulation of nutrient sources can also play an important role in the nutrient release and cycling. Hence, OMFs have been shown as an option for reusing organic waste (i.e., biosolid) with impacts on the nutrient release from low-solubility sources. It is noteworthy that OMFs properties should not be restricted solely to biosolids but also other organic sources or granulated fertilizers and our results can be used to state and test related hypothesis to explore organic waste and residues for sustainable nutrient management.

Conclusion

This work presents a study of the combination of organic and mineral sources (biosolids, rock phosphate, and potassium sulfate) on OMFs composition and its influence on the dynamics of nutrient availability. Using granulated organomineral fertilizers increased the efficiency of nutrient availability during the incubation period studied. Adding mineral sources to the OMFs increased the P and K efficiency index, compared to biosolid (with and without granulation), especially after 14 days. The role of granulation in the controlled release of K is highlighted in comparison with Potassium sulfate (not granulated), which is a highly soluble fertilizer and challenging to synchronize between the nutrient demand and its availability in the soil. Despite evaluating only a single source of each macronutrient (biosolid for N, rock phosphate for P, and potassium sulfate for K) in the formulation of OMFs, the observed EIs show that the presence of more than one macronutrient influences the dynamics of nutrient release. This was observed in regard to N mineralization, where OMFs containing NPK nutrients did not register N immobilization in any of the analyzed days. Furthermore, OMFs were also effective to decrease soil P immobilization from day 28 to day 112, compared to single P sources. The results herein indicate the potential that OMFs have to increase nutrients use efficiency and decrease agriculture reliance on mineral fertilizers.

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Authors contributions JBN-F has conceptualized, designed, and conducted the experiment; collected and processed the data; performed the data analysis; interpreted the results; wrote and edited the paper. FPC collected and processed the data; interpreted the results and wrote the paper. ACMA collected and processed the data; wrote and edited the paper. RCD assisted the data analysis, wrote, edited, and revised the text. NMAS assisted results interpretation, wrote, edited, and revised the text. EZ conceptualized the research and experiment; wrote, edited, and revised the text. All authors reviewed and approved the final version of the manuscript.

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Declarations

Conflict of interest The authors report that there are no competing interests to declare.

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