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Agronomic efficiency of organomineral fertilizer in sequential grain crops in southern Brazil

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Abstract

The use of organomineral fertilizers in agriculture instead of mineral fertilizers is a way to add organic compounds to the soil, potentially improving its properties and crop production. Our objective was to evaluate the agronomic efficiency of an organomineral fertilizer manufactured from poultry litter and mineral fertilizers. The experiment was carried out in a Humic Cambisol in the subtropical region of Brazil, with high organic matter content, low phosphorus content, and very high potassium content. The study consisted of six treatments: mineral fertilizer (monoammonium phosphate, KCl, and urea), at rates of 100 and 150% of the technical recommendation; organic fertilizer (poultry litter), at 100% rate; organomineral fertilizer (poultry litter + monoammonium phosphate), at rates of 100 and 150%; and control treatment (without fertilization). Between 2015 and 2017, common bean (*Phaseolus vulgaris*), wheat (*Triticum aestivum* L.), and corn (*Zea mays* L.) were sequentially cultivated. Before performing the experiment and at the end of the fourth crop, chemical properties of the soil were analyzed in the 0- to 10- and 10- to 20-cm layers. The use of fertilizers increased crop yield, but there was no difference between the three fertilizer sources or between the 100 and 150% rates of the technical recommendation. Chemical properties of the soil were altered in a similar manner with fertilization, regardless of the fertilizer source used. According to the results, the organomineral fertilizer can replace mineral fertilizers with equivalent performance.

1 | INTRODUCTION

Subtropical soils of southern Brazil are generally weathered, naturally acidic, and have low natural fertility (Bortoluzzi, Pérez, Ardisson, Tiecher, & Caner, 2015). The correction of the acidity and fertility of these soils is recommended for adequate plant yield. Nutrients commonly demanded in greater amounts are nitrogen (N), phosphorus (P), and potassium (K), which are part of the fertilization routine of agricultural crops of the aforementioned region (CQFS – RS/SC, 2016). These nutrients are supplied via soil fertilization whenever needed, and different mineral, organic, and/or organomineral sources may be used.

Overall, annual agricultural crops are fertilized with mineral sources, because of greater solubility (Herrera, Rodrigues, Teles, Barth, & Pavinato, 2016), concentration, and lower price per unit of the product when compared with

Abbreviations: AEI, agronomic efficiency index; CEC, cation exchange capacity; CONT, control treatment; MAP, monoammonium phosphate; MF, mineral fertilizer; OM, organomineral; PE, physiological efficiency; PL, poultry litter; PRNT, relative neutralizing power (%); SDMY, shoot dry matter yield; SOM, soil organic matter; TOC, total organic carbon; UE, use efficiency.

organic or mixed sources, which also leads to higher operational efficiency of fertilization. However, the high solubility of mineral fertilizers may cause nutrient losses, mainly N, because of volatilization and/or leaching (Lourenço, Ernani, Corrêa, Dal Molin, & Lourenço, 2016), P fixation (Borges et al., 2019), and leaching of K (Rosolem, Almeida, Rocha, & Bacco, 2018). Organic fertilizers are an alternative to soluble fertilizers, especially those originating from animal production (waste or manure) whose main characteristics are low nutrient concentration and slow rate of nutrient release (Antille, Sakrabani, & Godwin, 2014). However, the high rates of application required, operational feasibility of transport, and application limit the use of these fertilizers.

To circumvent the limitations of mineral or organic fertilizers, a way to increase the efficiency of fertilization is to mix organic sources of nutrients and mineral fertilizers, creating the so-called organomineral fertilizers (Antille et al., 2017; Borges et al., 2019; Frazão, Benites, Ribeiro, Pierobon, & Lavres, 2019; Sá et al., 2017). The addition of mineral fertilizers to organic compounds can improve the efficiency of nutrient utilization (Antille et al., 2017; Borges et al., 2019; Rosolem et al., 2018). Low molecular weight organic acids present in organic compounds can reduce P adsorption because these acids compete with phosphate for the adsorption sites on the soil colloids (Borges et al., 2019; Chien, Edmeades, McBride, & Sahrawat, 2014). However, there is no consensus on whether this mechanism — attributed to the organic fraction of the organomineral fertilizer—is effective or not in increasing the efficiency of nutrient use of the mineral fraction of such mixed fertilizer, as in some cases, there is no increase in fertilizer efficiency (Chagas, Guelfi, Emrich, Silva, & Faquin, 2016; Chien et al., 2014; Frazão et al., 2019). Conversely, there are small increases in fertilizer efficiency in other cases (Herrera et al., 2016; Hopkins, Fernelius, Hansen, & Eggett, 2018). When compared with the response of mineral fertilizers, the crop response to organomineral fertilizers is quite variable; according to the literature, there are gains (Deeks et al., 2013; Frazão et al., 2019), losses (Antille et al., 2017; Frazão et al., 2019), or equivalent efficiency (Corrêa et al., 2018). This variation pattern stresses the need for further studies on varying soil and climate conditions, especially in field conditions.

Regardless of the nutrient source being used, the increase in the amount of fertilizer above the recommended rates is not effective in generating economically significant yield gains (Antonangelo, Alleoni, Oliveira, & Zhang, 2019; Chagas et al., 2016; Vieira, Fontoura, Bayer, Moraes, & Carniel, 2015), except if the nutrient source is not promptly available for plants. Additionally, nutrient uptake below the added quantities can lead to gradual accumulation in the soil, such as the case of P (Barrow, 2015; Nobile, Bravin, Tillard, Becquer, & Paillat, 2018; Roy et al., 2017), or it may result in losses within the system (Fischer, Pothig, Gucker, & Venohr, 2018), either by volatilization, leaching, or runoff. However, crop yields have increased over the years for several reasons, such as fertilizer addition, genetic improvement, and improvement in plant distribution (South, Cavanagh, Liu, & Ort, 2019). Consequently, critical levels of certain nutrients may have been altered, supporting the perspective that higher fertilization rates may, in some cases, increase the yields.

Core Ideas
- Organomineral fertilizers need a technical evaluation of their effectiveness.
- In equal nutrients rates, the grain yields are similar among the fertilizers
- Application of nutrients rates above the recommended is not technically effective.
- In equal rates, fertilizers alter the chemical properties of the soil similarly.
- Opting for an alternative fertilizer must consider availability, price, and logistics.

Within this context, the main hypothesis of our study is based on the assumption that organomineral fertilizers, because of their gradual release of nutrients, will increase the yield of crops by increased efficiency of nutrients uptakes. Our objectives are (a) to evaluate the efficiency of an organomineral fertilizer in the yield of grain crops in southern Brazil and (b) to evaluate the effect of fertilization with organomineral fertilizer on soil chemical properties.

2 | MATERIAL AND METHODS

2.1 | Characterization of the experimental area

The experiment was conducted from 2015 to 2017 at the experimental farm of the Santa Catarina State University (UDESC), Santa Catarina state (27°44′54″S, 50°05′08″W, and 884 m of altitude), in southern Brazil. The local climate is classified as Cfb, according to the Koppen Climate Classification, characterized as temperate with mild summer, and rainfalls evenly distributed throughout the months of the year, without the presence of dry season.

The soil is classified as a Humic Cambisol (FAO, 1998). Prior to the installation of the experiment, the experimental area was kept under native vegetation, predominantly composed of creeping grasses, as the genus *Cynodon* and *Festuca*. Soil samples were collected in the 0- to 20-cm layer and analyzed prior the experiment installation, and the results were: 28, 31, and 41% clay, silt, and sand, respectively; pH (H_2O – 1:1) 4.6; pH SMP (Shoemaker–McLean–Pratt Buffer): 4.9; 5.1% organic matter (Walkley–Black method);

7.9 and 186.8 mg dm^{-3} of available P and K extracted by Mehlich-1; 2.9, 5.6, and 3.2 $cmol_c$ dm^{-3} of exchangeable Al, Ca, and Mg extracted by 1 M KCl; 15.6, 10.9, 13.9, and 26.5 $cmol_c$ dm^{-3} of H+Al, sum of bases, effective cation exchange capacity (CEC), and CEC at pH 7; and 21.5 and 41.1% of aluminum saturation and base saturation. Before cultivation, 10.7 Mg ha^{-1} of dolomitic limestone (90% relative neutralizing power [PRNT], 29% Ca oxide, and 19% Mg oxide) was added to increase soil pH to 6.0. All the limestone was evenly distributed (in a single application) on the soil surface, and subsequently incorporated in the 0- to 20-cm layer with moldboarded once and disked twice.

2.2 | Experimental design and description of treatments

The experiment was conducted in a randomized block design with six treatments and four replications. The treatments were: 100% of the N–P–K recommendation in the form of organomineral fertilizer (OM 100); 100% of the N–P–K recommendation supplied by poultry litter (PL 100); 100% of the N–P–K recommendation in the form of mineral fertilizer (MF 100); 150% of the N–P–K recommendation in the form of mineral fertilizer (MF 150); 150% of the N–P–K recommendation in the organomineral form (OM 150); and control treatment without fertilization (CONT). Rates of the fertilizers refer to the recommended rate for the crops to reach the yield of 2.5 Mg ha^{-1} of common bean (*Phaseolus vulgaris*), 3 Mg ha^{-1} of wheat (*Triticum aestivum* L.), and 6 Mg ha^{-1} of corn (*Zea mays* L.), according to the local fertilizer recommendation manual (CQFS-RS/SC, 2016). The amounts of N, P_2O_5, and K_2O applied in the treatments with 100% of the fertilizer rate (OM 100, PL 100, and MF 100) were 43.5, 70.0, and 43.5 kg ha^{-1} for bean, 23.1, 45.0, and 28.0 kg ha^{-1} for wheat and 40.0, 64.0, and 40.0 kg ha^{-1} for corn, respectively. The fertilizer sources used were PL as organic fertilizer, and monoammonium phosphate (MAP), urea, and muriate of potash (KCl) as mineral sources. The organomineral fertilizer consisted of the industrial mixture and granulation of 60% w/w PL plus 40% w/w MAP (Table 1). For treatments with organic or organomineral fertilizer use, the rate was based on the recommendation of P, with the additional amounts required of N and K being supplied with urea and KCl, respectively. Table 2 shows the total amount of N, P, and K applied into the four crops, the total amount exported by the grains, and balance between the inputs and outputs.

2.3 | Crops and management

The crop rotation used was common bean (2015–2016), wheat (2016), corn (2016–2017), and wheat (2017), sown on 14 Dec. 2015, 21 July 2016, 11 Jan. 2017, and 29 June 2017 (Figure 1), respectively, in plots of 12 m^2 (3 by 4 m).

The seeding operation was similar for all crops. The opening of rows, fertilization, and distribution of the seeds were manually performed. Total P and K nutrients were supplied preplant, whereas N fertilization was divided into preplant fertilization and side dressed. The bean (Uirapuru cultivar) was sown at 0.5-m row spacing, with a density of 200,000 seeds ha^{-1}. The wheat (BRS Marcante cultivar), was sown at 0.2-m row spacing and density of 330 seeds m^{-2}. The corn (BR 145 cultivar) was sown at a 0.5-m row spacing and density of 60,000 seeds ha^{-1}. During each cropping season, phytosanitary treatments were carried out to control invasive plants, pests, and diseases whenever necessary.

2.4 | Crop and soil evaluation

The response of the crops to the treatments was evaluated by measuring the following parameters: shoot dry matter yield (SDMY); grain yield; cumulative contents and amounts of N, P, K, Ca, and Mg in the shoot; and contents and exported amounts of N, P, K, Ca, and Mg by the grains. The SDMY was evaluated by collecting one linear meter of plants in the central row of each experimental plot. The material was weighed after drying in a forced-ventilation oven at 60 °C. The methodology for evaluating crop grain yield varied according to plant species. Common bean was harvested in a 2.5-m^2 area in the central region of the plot, wheat was harvested in a 3.6-m^2 area in the central part of each plot, and corn was collected from one linear meter of plants in the central part of the plot. After harvesting, grains were weighed and yield was calculated with grain moisture corrected to 13%. The plant material used to evaluate the SDMY and the harvested grains were ground in a Wiley mill (Thomas Scientific, Swedesboro, NJ) and digested by wet digestion with sulfuric acid and hydrogen peroxide (Tedesco, Gianello, Bissani, Bohnen, & Volkweiss, 1995), and the concentrations of P, K, N, Ca, and Mg were determined. In addition, some other variables were measured in each crop season. For bean, the number of grains per plant, number of pods, number of grains per pod, and 1,000-grain weight were evaluated. For wheat, plant height at the tillering stage, plant height at the stage of full flowering, and 1,000-grain weight were evaluated. The hectoliter mass was determined only in the second wheat cropping season. For corn, plant height at the stage of full flowering and dry matter of shoots, plant height at the tillering stage at full flowering, and 1,000-grain weight were evaluated.

Soil samples were taken from the 0- to 10- and 10- to 20-cm depths four times during the experiment. The first sampling was performed about 6 mo after incorporation of limestone and prior to the implantation of the experiment

TABLE 1 Chemical characterization of the fertilizers used in the experiment. Values represent the average amounts for each fertilizer used

Characteristic	Poultry litter	MAP[a]	Organomineral	KCl	Urea
pH	8.7	–	5.8	–	–
C, % w/w	34.1	–	18.7	–	–
N, % w/w	2.3	9.0	5.8	–	45.0
P_2O_5, % w/w	3.7	48.0	21.0	–	–
P_2O_5 SW, % w/w	1.3	45.3	10.8	–	–
P_2O_5 SCA 2 % w/w	1.9	44.1	16.0	–	–
K_2O, % w/w	2.3	0.1	1.6	58.0	–

[a]MAP, monoammonium phosphate; SW, soluble in water; SCA 2%, soluble in 2% w/v citric acid.

TABLE 2 Amounts of added and exported N, P, and K and the balance (input minus output) in each treatment for the sum of the four sequential crops. Values following treatment names indicate % recommended rate

Treatment	Total applied			Total exported by grains			Balance		
	N	P	K	N	P	K	N	P	K
	kg ha^{-1}								
OM 100[a]	263.7	97.6	115.7	387.5	53.0	112.2	−123.8	44.6	3.5
PL 100	263.7	97.6	115.7	336.4	50.8	108.1	−72.7	46.8	7.6
MF 100	263.7	97.6	115.7	369.0	47.4	113.2	−105.3	50.2	2.5
MF 150	328.5	146.0	174.3	414.0	59.5	124.4	−85.5	86.5	49.9
OM 150	328.5	146.0	174.3	410.4	57.7	119.8	−81.9	88.3	54.4
CONT	134[b]	0.0	0.0	221.3	23.1	56.4	−87.3	−23.10	−56.4

[a]OM, organomineral; PL, poultry litter; MF, mineral fertilizer; CONT, control.
[b]This refers to the total amount of N applied (pre-plant + side dressing) in the crops of wheat and corn, whose amount was equal for all treatments.

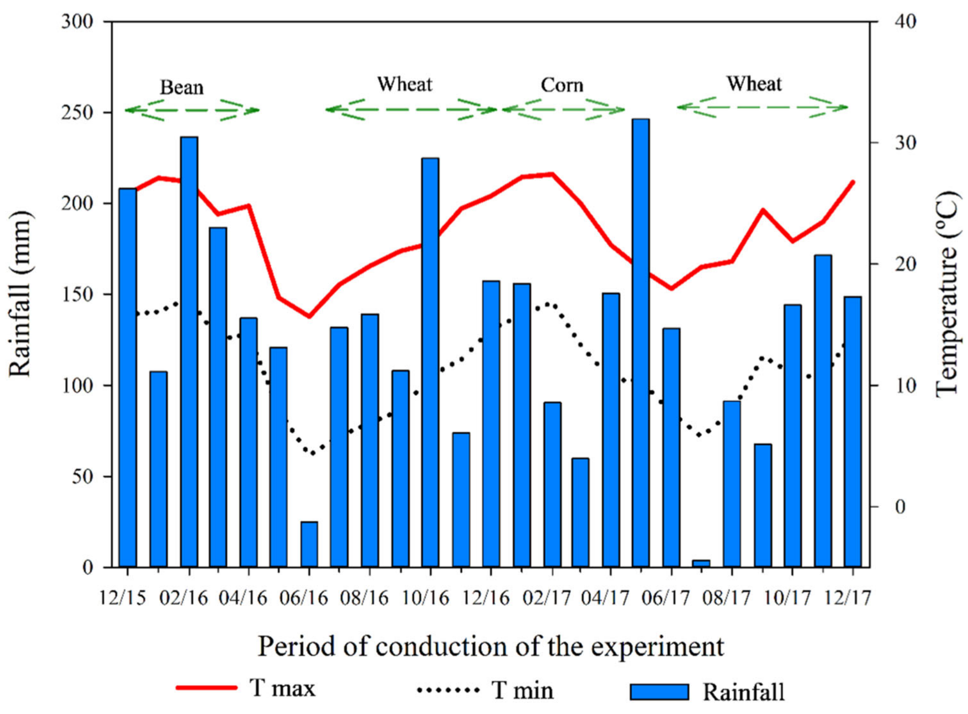

FIGURE 1 Maximum (T max) and minimum (T min) average temperatures in each month, and monthly sum of rainfall during the 2-yr experiment

(Dec. 2015), whereas the others were performed after harvesting of bean (Apr. 2016), wheat (Dec. 2016), and wheat (Nov. 2017). After sampling, the samples were dried and sieved in a 2-mm mesh with subsequent analysis of the following parameters: pH H_2O, determined in a soil/water 1:1 ratio; pH SMP, in soil/water/SMP solution ratio of 1:1:0.5; exchangeable contents of Ca, Mg, and Al, extracted with 1 M KCl, and determined by atomic absorption spectrophotometry (AAnalyst 200 apparatus, PerkinElmer, Waltham, MA); available values of P and K, extracted with the solution of Mehlich-1 (0.0125 M H_2SO_4 and 0.050 M HCl), determined by colorimetry at a wavelength of 882 nm (Murphy & Riley, 1962) and flame photometry, respectively; and total organic carbon content (TOC), extracted by a sulfochromic extractant. The methods of analysis of elements mentioned above were based on the methodologies described in Tedesco, Gianello, Bissani, Bohnen, and Volkweiss (1995). The values of CEC pH 7 and base saturation were calculated and the values of H+Al were determined based on pH–SMP results, using Equation 1 (CQFS-RS/SC, 2016):

$$\mathrm{H+Al}\left(\mathrm{cmol_c dm^{-3}}\right) = \left[\exp\left(10.665 - 1.1483\mathrm{SMP}\right)\right]/10 \quad (1)$$

Agronomic Efficiency Index (AEI) of fertilizers was calculated based on the grain yields of the crops, using Equation 2 (Silveira, Pegoraro, Kondo, Portugal, & Resende, 2018):

$$\mathrm{AEI}\,(\%) = \frac{(\text{treatment yield} - \text{control yield})}{(\text{MF100yield} - \text{control yield})}100 \quad (2)$$

Use efficiency (UE) of the applied P (PUE), K (KUE), and N (NUE) from fertilizers were calculated based on grain yield of the crops, using the equation proposed by Syers et al. (2008):

$$\mathrm{UE}\left(\mathrm{kg kg^{-1}}\right) = \frac{\text{treatment yield} - \text{control yield}}{\text{total amount of nutrient used (N, P, or K)}} \quad (3)$$

Moreover, physiological efficiency (PE) was calculated to relate grain yield to the amount of nutrient accumulated in the shoot of the plants. PE was calculated for the amount of P (PPE), K (KPE), and N (NPE) accumulated in the plant, using Equation 4, proposed by Restelatto, Pavinato, Sartor, Einsfeld, and Baldicera (2014):

$$\mathrm{PE}\left(\mathrm{kg kg^{-1}}\right) = \frac{\text{treatment yield } x - \text{control yield}}{\text{cumulative nutrient SDMYtreatment} - \text{cumulative nutrient SDMY control}} \quad (4)$$

The control yield, cited in Equations 2, 3 and 4, refers to the results of treatment without fertilization (CONT), and the MF 100 yield, cited in Equation 2, refers to the results of treatment with 100% of the N–P–K recommendation in the form of mineral fertilizer, which is considered the traditional treatment adopted by farmers.

2.5 | Statistical analysis

Collected data were submitted to the Shapiro–Wilk normality test to meet the assumptions of normality and homoscedasticity; no transformation was needed to the data presented. Subsequently, the data were submitted to analysis of variance (ANOVA). Whenever significant, means were compared by Tukey HSD test ($p < .05$). Analyses were performed with the software Sisvar 5.6 (Ferreira, 2014).

3 | RESULTS AND DISCUSSION

During the cropping season of bean (2015–2016), first wheat (2016), corn (2016–2017), and second wheat (2017), rainfall amounts were 673, 592, 331, and 461 mm , respectively (Figure 1). Except for the second wheat crop, cumulative rainfall volumes were considered adequate for good development and yield of the crops. Temperatures were particularly low during the reproductive phase of corn, with one frost occurrence, which harmed the corn yield.

Table 2 presents an overview of the nutrient balance in the system following the sequence of four crops. It is noted that only N had a negative balance, in which the quantity exported was in higher quantities than added via fertilizer. On the other hand, P and K had a positive balance, which was more expressive in the treatments where 150% of the recommended rate was applied (FM 150 and OM 150). Nutrient balance data N, P, and K are considered following the discussion of the results.

3.1 | Dry matter production and grain yield

Shoot dry matter yield (Table 3) and grain yield (Figure 2) of the four fertilized crops were higher in fertilized treatments than in the control, except for corn cultivation, in which the addition of fertilizers had no significant effect. The treatments OM 100, PL 100, MF 100, MF 150, and OM 150 increased the SDMY by 45, 43, 40, 59, and 62% compared to the control, respectively. The yield in the treatments OM 100, PL 100, MF 100, MF 150, and OM 150 were 84, 68, 77, 83, and 87% higher than the control, respectively. Higher SDMY may be due to fertilization (Silveira et al., 2018) and commonly has a positive correlation with grain yield. Moreover, the largest input of vegetal biomass contributes to the stabilization and/or increase in the content of soil organic matter (SOM; Antille et al., 2017), which increases soil quality (Borges et al., 2019; Fontoura et al., 2019).

TABLE 3 Shoot dry matter yields of beans, wheat (two harvests), and corn produced in response to fertilizers used (source followed by % recommended application rate) in a Humic Cambisol

Treatment	Beans 2015–2016	Wheat 2016	Corn 2016–2017	Wheat 2017	Cumulative
	Dry matter yield				
	kg ha^{-1}				
OM 100[a]	6,283.4a[b]	10,559.8a	16,516.8ns	6,670.0ab	40,030.0a
PL 100	5,461.4a	9,728.5a	14,671.7	6,823.5ab	36,685.1a
MF 100	5,178.5ab	10,077.6a	14,627.0	6,032.5ab	35,915.6a
MF 150	6,640.0a	11,292.9a	14,641.9	8,363.6a	40,938.4a
OM 150	6,699.9a	11,241.9a	15,757.9	7,836.2a	41,535.9a
CONT	2,718.9b	6,332.10b	13,124.2	3,532.8b	25,707.9b
CV, %	19.3	12.5	17.3	23.3	9.9

[a]OM, organomineral; ns, statistically nonsignificant; PL, poultry litter; MF, mineral fertilizer; CONT, control; CV, coefficient of variation.

[b]Averages followed by different letters in the columns differ from each other according to Tukey HSD test ($p < .05$).

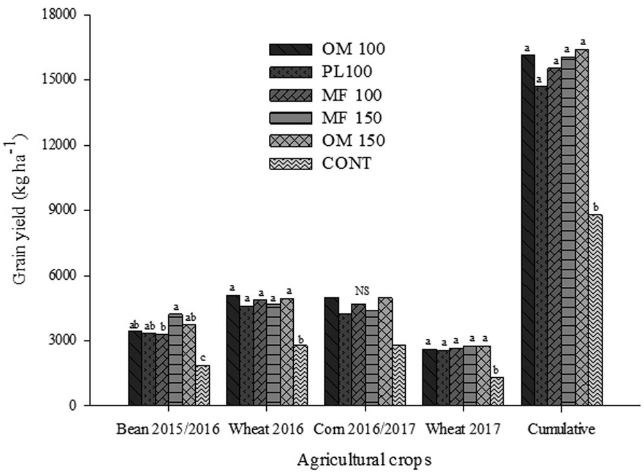

FIGURE 2 Grain yields per harvest and cumulative yield of beans, wheat (two harvests), and corn produced in response to treatments (fertilizer source followed by % recommended rate) in a Humic Cambisol. Averages followed by different letters in the bars (representing each crop) differ from each other according to Tukey HSD test (p < .05). OM, organomineral; PL, poultry litter; MF, mineral fertilizer; CONT, control, no fertilizer; NS, statistically nonsignificant. The values of coefficients of variation were: 14.0, 8.3, 30.2, 15.5, and 9.3% for bean, wheat 2016, corn, and wheat 2017 crops and cumulative yield, respectively.

Organomineral, organic, and mineral fertilizers presented the same agronomic performance, corroborating the results found by other studies (Corrêa et al., 2018; Deeks et al., 2013; Frazão et al., 2019). These results indicate that possible differences in the nutrient-release dynamics do not influence the productivity of crops in the conditions studied. The experimental site is located in a high-altitude region of southern Brazil (900 m asl), with high SOM content (Bortoluzzi et al., 2015), which may have attenuated the beneficial effect of organic materials present in the organomineral and organic fertilizer, as the SOM content is much higher than those provided via fertilization (Sá et al., 2017).

Despite the addition of nutrients above the recommended rate (OM 150, MF 150), there was no significant increase in grain yield, regardless of the source used, with the exception of the 21.4% increase in bean yield from the MF 150 treatment compared with the MF 100 treatment. Despite possible small increases in yield, rates of fertilizers above the recommended rate are unfeasible because they bring virtually no economic gains (CQFS – RS/SC, 2016; Tian et al., 2019; Vieira et al., 2015).

3.2 | Efficiency indices

The AEI for SDMY (Figure 3a) and the AEI of the nutrients P (Figure 3b), N (Figure 3c), and K (Figure 3d) accumulated in the plant shoots throughout the four crops were higher in the treatments MF 150 and OM 150, OM 100, and CA 100 than the MF 100 treatment, which is considered the standard. For grain yield and P, N, and K nutrients exported by these grains, treatments MF 150, OM 150, OM 100, and CA 100 presented higher AEI than MF 100. Treatments with nutrient input above the recommended rate (MF 150 and OM 150) had the highest AEI values for all analyzed variables, with more significant differences than the standard treatment for the variables relative to vegetal biomass (yield and nutrients accumulated in the shoots). These results indicate that excessive nutrient input may be more effective in increasing plant biomass accumulation, but this is not equivalently reflected in grain yield, possibly because of a "luxury uptake" of nutrients by the plant (Fontoura et al., 2019).

Based only on AEI values of the treatments with equivalent rates of nutrients (OM 100, PL 100, and MF 100), the OM fertilizer had slightly higher efficiency than the organic and mineral sources. The association of the potential benefits of organic waste with the high concentration of nutrients

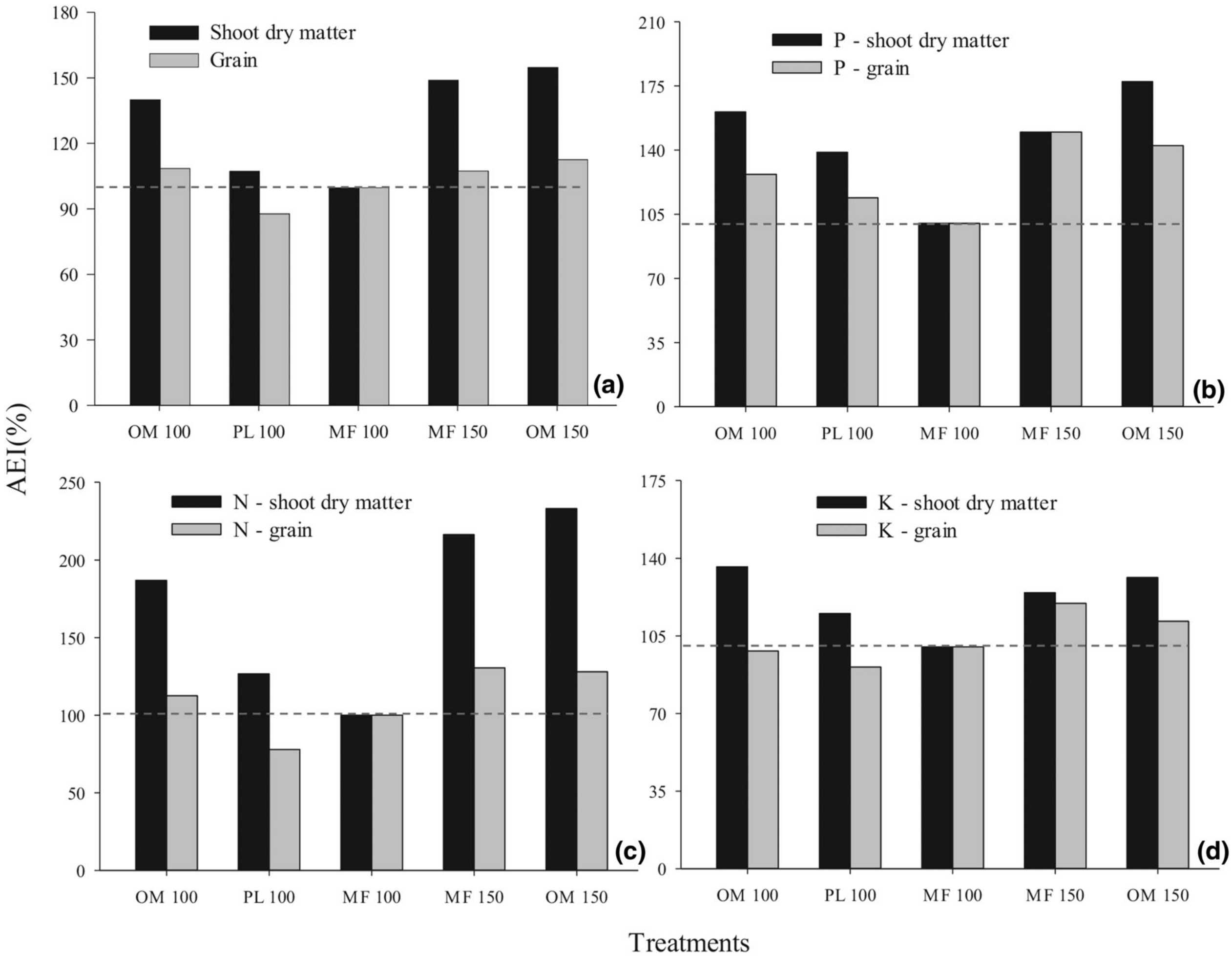

FIGURE 3 Agronomic Efficiency Index (AEI) for cumulative dry mass and grain yield (a), and cumulative total amounts of P (b), N (c), and K (d) in the shoot of beans, wheat (two harvests), and corn, in response to treatments (fertilizer source followed by % recommended rate) in a Humic Cambisol. OM, organomineral; PL, poultry litter; MF, mineral fertilizer; CONT, control, no fertilizer. Dashed line represents AEI of 100%

present in MF may result in greater efficiency of OM fertilizers (Antille et al., 2014; Borges et al., 2019). In addition, the presence of the organic fraction could reduce the solubility of the fertilizer, resulting in a more gradual release of nutrients into the soil (Grohskopf et al., 2019; Mumbach et al., 2019). However, these benefits were not effective in increase grain yield (Figure 2), thus using OM fertilizers may be economically unfeasible. However, it is noteworthy that the treatments OM 100 and PL 100 presented higher values of AEI in the parameters SDMY and nutrient accumulation than FM 100, since these two add equivalent rates of N, P, and K. The presence of the organic component and micronutrients in the OM fertilizer and in the PL may bring some advantage to plant growth in comparison to strictly mineral fertilization (Grohskopf et al., 2019), but with no consequence in grain yield.

The highest nutrient UE was found for P (PUE), followed by K (KUE) and N (NUE; Table 4). Higher response to phosphate fertilization occurs when there is low availability of the nutrient in the soil (Frazão et al., 2019), as in the present study. Prior to cultivation, P content was classified in the "very low" range (CQFS – RS/SC, 2016). On the other hand, K content was classified as "very high," and organic matter, used as a criterion for N recommendation, was classified as "high" (CQFS – RS/SC, 2016). Among the treatments, differences were found in the wheat seasons: the highest values of PUE, KUE, and NUE were found in treatments with 100% fertilization (OM 100, CA 100, and FM 100) compared with treatments with 150% fertilization (OM 150 and FM 150). These results indicate a reduction in the technical efficiency of fertilization when in rates above the recommendations (Chagas et al., 2016).

For the UE of cumulative yield, regardless of nutrient, higher values were found for MF 100 than any other tested treatments (Table 4). The lowest UE for the treatments OM 100, CA 100, MF 150, and OM 150, in comparison to MF 100, reflects the results shown in Figure 3, that is, the higher SDMY and consequently, the greater accumulation of

TABLE 4 Use efficiency of P (PUE), N (NUE), and K (KUE) and physiological efficiency of accumulated P (PPE), N (NPE), and K (KPE)for bean, wheat (two harvests), and corn in response to treatments (fertilizer source followed by % recommended rate) in a Humic Cambisol

Treatment	PUE	NUE	KUE	PPE	NPE	KPE
	———kg grains kg^{-1} applied nutrient———			—kg grains kg^{-1} nutrient accumulated in the plant—		
			2015–2016 Bean harvest			
OM 100[a]	46.1ns	30.8ns	38.0ns	195.0c[b]	22.3ns	15.5ns
PL 100	55.5	38.7	45.5	245.0c	32.4	17.1
MF 100	47.4	33.2	39.9	338.6bc	34.6	16.5
MF 150	51.3	36.0	43.3	690.8a	53.1	27.2
OM 150	40.7	28.6	34.3	521.3ab	29.1	30.3
CV, %	17.3	16.8	17.0	27.8	47.1	72.8
			2016 Wheat harvest			
OM 100	123.2a	38.6ns	111.8a	253.7ab	113.3a	68.8ns
PL 100	93.1bc	30.4	86.1bc	151.1bc	62.5ab	42.7
MF 100	106.8ab	34.9	98.7ab	315.1a	46.7b	50.2
MF 150	63.9d	25.8	58.0d	107.1c	22.3b	51.6
OM 150	72.9cd	29.4	66.1cd	165.4bc	38.4b	48.0
CV, %	12.9	18.4	12.9	27.3	42.1	48.2
			2016–2017 Corn harvest			
OM 100	96.9ns	67.2ns	81.2ns	166.0b	29.6b	25.4b
PL 100	80.6	54.0	62.9	340.6b	214.6ab	81.6a
MF 100	103.8	65.4	78.6	673.8a	375.7a	63.1ab
MF 150	59.6	39.0	73.3	318.7b	31.3b	53.9ab
OM 150	55.1	37.8	45.4	136.8b	20.3b	31.8ab
CV, %	27.6	34.0	51.4	38.2	66.3	46.3
			2017 Wheat harvest			
OM 100	53.0ab	51.1ab	41.4ab	261.5ns	34.3b	38.1ns
PL 100	43.3ab	41.4ab	34.6ab	222.7	81.5a	37.0
MF 100	60.1a	58.1a	48.0a	241.2	41.8b	41.6
MF 150	38.5b	37.2b	30.6b	151.6	20.9b	21.1
OM 150	41.2ab	42.4ab	33.3ab	176.5	20.2b	20.8
CV, %	19.0	19.2	18.8	31.3	37.1	42.3
			Cumulative			
OM 100	75.3a	27.9ns	63.5a	178.1ns	31.9ns	28.6ns
PL 100	60.9ab	22.5	51.4ab	173.0	39.4	28.9
MF 100	69.1ab	25.6	58.3ab	278.4	64.4	96.6
MF 150	49.8b	22.1	41.7b	188.0	25.8	30.0
OM 150	52.2ab	23.2	43.7ab	167.1	24.1	33.6
CV, %	17.0	16.4	17.0	32.1	61.8	131.7

[a]OM, organomineral; NS, nonsignificant; PL, poultry litter; MF, mineral fertilizer; CV, coefficient of variation.
[b]Averages followed by different letters in the columns differ from each other according to Tukey HSD test ($p < .05$).

nutrients in the plant, did not result in increase of grain yield in these treatments.

The PE of using nutrients accumulated in the plant showed similar behavior to the one found for UE; the highest values were found for P (PPE), followed by N (NPE) and K (KPE; Table 4). Variation between treatments followed a different pattern than UE; in the first cropping season, the highest PPE was found for the treatments with 150% fertilization (OM 150 and MF 150), compared with the 100% treatments (OM 100, PL 100, and MF 100). This is possibly due to the initial reduced availability of P, which leads to greater increases in grain yield by increasing fertilization (Vieira et al., 2015). However, for the subsequent crops, the highest values of PPE, NPE, and KPE were found in the treatments with 100% fertilization (OM 100, PL 100, and MF 100). Based on the different behavior among the crops, it was found that nutrient

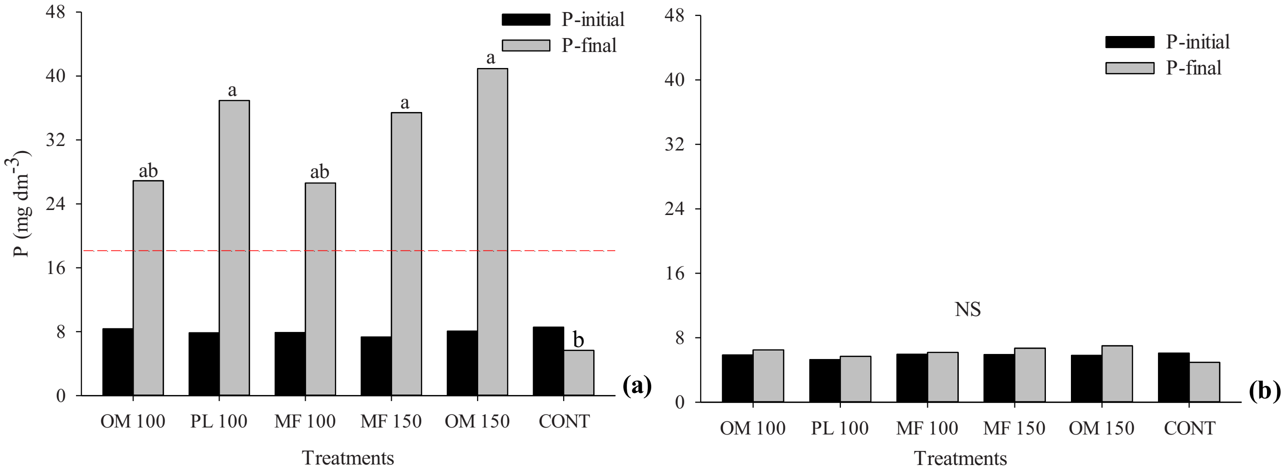

FIGURE 4 Contents of available P extracted by Mehlich-1 in soil samples collected prior to the implantation of the experiment (P-initial) and at the end of the experiment (P-final), in the 0- to 10- (a) and 10- to 20-cm (b) depths of the soil with different treatments (fertilizer source followed by % recommended rate) in a Humic Cambisol. Averages followed by different letters in same-colored bars differ from each other according to Tukey HSD test ($p < .05$). OM, organomineral; PL, poultry litter; MF, mineral fertilizer; CONT, control, no fertilizer; NS, statistically nonsignificant. The values of coefficients of variation were: 40.1 and 17.1% for the 0- to 10- and 10- to 20-cm layers, respectively. Red dashed line represents adequate P content in the soil (CQFS – RS/SC, 2016)

accumulation in the soil, especially in treatments that received fertilization above the recommended rate, reduces plant use efficiency (Antonangelo et al., 2019; Restelatto et al., 2014). Fertilizations that exceed plant demand reflect in increased nutrient content in the soil, especially of P (Tian et al., 2019), which is susceptible to soil fixation (Barrow, 2015) and losses by runoff (Fischer et al., 2018). Nitrogen and K surpluses also tend to be lost from the soil system; N by volatilization or leaching (Lourenço et al., 2016), and K by leaching (Rosolem et al., 2018).

3.3 | Changes in the chemical properties of the soil

There was an increase in P availability in the treatments that received fertilizers, but it was restricted to the 0- to 10-cm layer (Figure 4a). Regardless of the sources and rates tested, fertilization increased P content in the soil at the level considered as adequate (CQFS – RS/SC, 2016). The highest *P*-values available in the 0- to 10-cm layer were found in the treatments OM 150, PL 100, and MF 150, and these were statistically higher than those in the control. Treatments with addition of 100% of fertilizer rates resulted in similar P concentrations in the soil, indicating that the presence of organic fractions in the OM fertilizer and in the PL did not result in greater availability of P. Organic compounds, in addition to the possible reduction in fertilizer solubility, could reduce the amount of P adsorbed on soil colloid particles since soluble forms of carbon and P can compete for adsorption sites (Hue, 1991). This apparent lack of effectiveness may be due to the reduced amount of organic compounds present in OM fertilizers, in addition to the high organic matter content originally present in the soil (Sá et al., 2017).

The accumulation of P in the surface layer of fertilized plots at the end of the four cropping seasons reflects the positive balance of this nutrient (Table 2), in which only 45, 48, 51, 59, and 60% of the applied P was exported in the treatments OM 100, CA 100, FM 100, MF 150, and OM 150, respectively. The reduced utilization of the applied P reflects the affinity of this element with the colloidal fraction of the soil (Bortoluzzi et al., 2015). This increase in the P "legacy" in the soil throughout frequent fertilizations can gradually increase the use efficiency of P applied in future crops (Nobile et al., 2018; Roy et al., 2017) due to chemical alterations in the soil, such as the increase of negative electrical potential, saturation of sorption sites, and consequent reduction in the P-sorption (Barrow, 2015). Moreover, the low percentage of utilization of the applied P may be justified by the buffering from organic forms of P, which are not extracted by Mehlich-1 method (Steffens, Leppin, Luschin-Ebengreuth, Yang, & Schubert, 2010). The absence of alteration of *P*-values in the subsurface layer of the soil is due to the surface deposition of fertilizers, about 5 cm below the surface, in addition to the reduced mobility of the nutrient in the soil (Nunes, Sousa, Goedert, & Vivaldi, 2011).

The available K concentration in the 0- to 10-cm layer of the soil increased at the end of the study, in the treatments with fertilization (Figure 5). The soil K status in the beginning and after the end of this study in the fertilized plots is considered adequate (CQFS – RS/SC, 2016). The initial and final contents of K remained relatively unchanged, except for

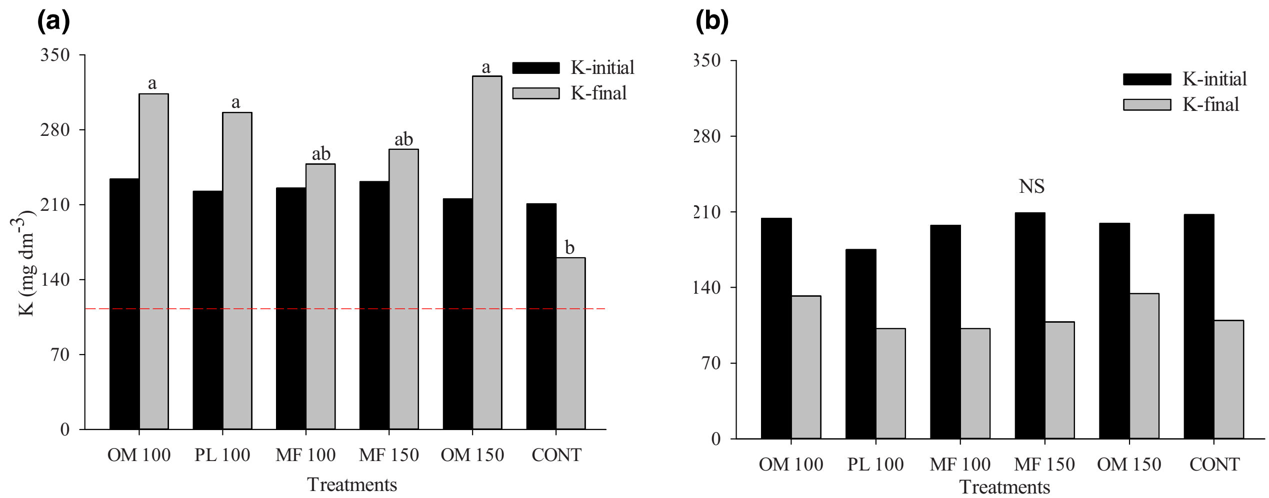

FIGURE 5 Contents of available K extracted by Mehlich-1 in soil samples collected prior to the implantation of the experiment (K-initial) and at the end of the experiment (K-final), in the 0- to 10- (a) and 10- to 20-cm (b) depths of the soil with different treatments (fertilizer source followed by % recommended rate) in a Humic Cambisol. Averages followed by different letters in same-colored bars differ from each other according to Tukey HSD test ($p < .05$). OM, organomineral; PL, poultry litter; MF, mineral fertilizer; CONT, control, no fertilizer; NS, statistically nonsignificant. The values of coefficients of variation were: 16.9 and 30.3% for the layers 0-10 and 10-20 cm, respectively. Red dashed line represents adequate K content in the soil (CQFS – RS/SC, 2016)

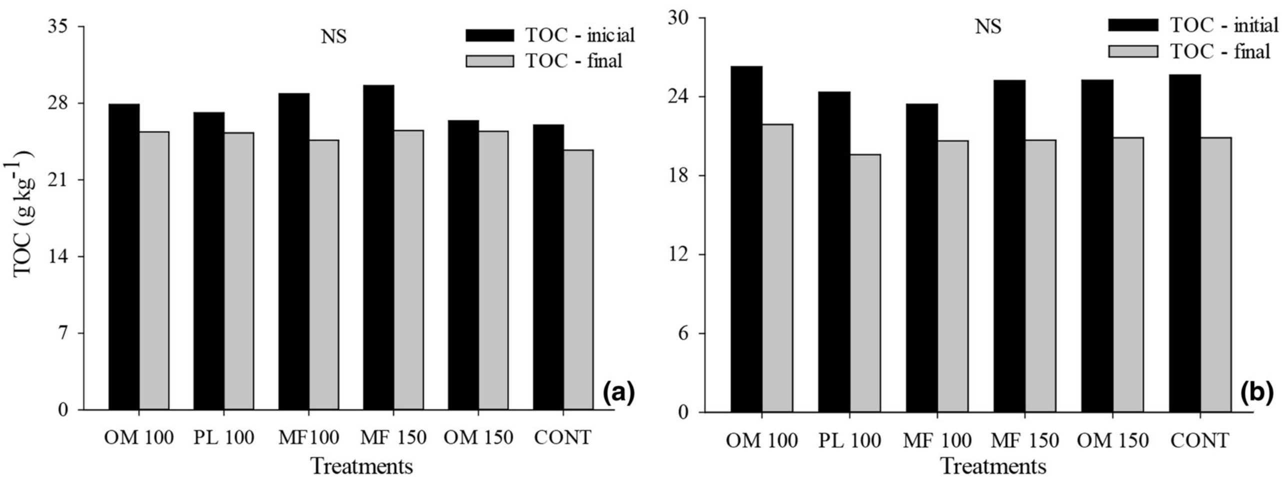

FIGURE 6 Contents of total organic carbon (TOC) in soil samples collected prior to the implantation of the experiment (TOC-initial) and at the end of the experiment (TOC-final), in the 0- to 10- (a) and 10- to 20-cm (b) depths of the soil with different treatments (fertilizer source followed by % recommended rate) in a Humic Cambisol. NS, statistically nonsignificant ($p < .05$); OM, organomineral; PL, poultry litter; MF, mineral fertilizer; CONT, control, no fertilizer. The values of coefficients of variation were: 6.4 and 7.9% for the 0- to 10- and 10- to 20-cm layers, respectively

the significant reduction in the soil contents of the control treatment. There was no differences in K status among treatments fertilized, because even in organic sources of fertilizers, such as PL, K is present in soluble forms, thereby reducing the chance of a differentiated effect of fertilizer sources on the release and availability of this nutrient in the soil (CQFS – RS/SC, 2016). In the 10- to 20-cm layer, similarly to what happened with the available P, there were no differences among the treatments. However, there was an important reduction in the exchangeable K of the soil at the end of the fourth cropping season. The expressive reduction in K in the subsurface layer can be explained by deposition and retention of the nutrient in the surface layer of the soil, due to the high CEC in the soil (Rosolem et al., 2018) and plant uptake, as the root system usually grows on the top layer of the soil.

No differences were found in TOC content in the 0- to 10-cm layer (Figure 6a), nor in the 10- to 20-cm layer (Figure 6b) with respect to the applied fertilizers. The lack of influence of fertilization sources on TOC content may be due to the inexpressive amount of carbon added to the soil through fertilizers, when compared with the total amount of original organic matter of this soil type (Table 1). Under average conditions, the soil from the arable layer of 0–20 cm, presents around 58 Mg ha^{-1} of TOC, whereas the annual addition of TOC through OM fertilizer and PL was 0.10 and 1.03 Mg ha^{-1}, respectively. Based on these values, the annual addition of C by OM fertilizers and PL, in comparison to the amounts already present in the soil, represents 0.2 and 1.8%, respectively. There was an observed decrease in TOC after the fourth successive crop in both sampled soil layers compared to the beginning of the experiment. Reduction in TOC content over time and after successive crops is expected, especially under the conditions of the present study, in which the soil was a natural pasture in a steady state of inputs an outputs of carbon before the experiment, and was disturbed by tillage. The adoption of mechanical intervention practices results in a significant reduction in the amount of organic matter in the first years of cultivation (Yang, Tilman, Furey, & Lehman, 2019). It is noteworthy, however, that such reduction is nonsignificant, because of the prevalence of mild temperatures in high altitude locations in the Southern region of Brazil, which leads to a slow rate of SOM decomposition (Bortoluzzi et al., 2015). Moreover, this reduction of SOM content notably contributed to crop yields, as the balance (addition minus extraction) of N at the end of the four crops (Table 2) was negative for all treatments, which means that part of the nutrient exported by crops came from the mineralization of SOM (Miller & Geisseler, 2018).

Based on the results of plant yields and chemical properties of the soil, the OM fertilizer did not present higher efficiency in comparison to the other sources. Therefore, it is noteworthy that, under equivalent rates, the evaluated fertilizers are equally efficient, and the choice of one of these fertilizer sources should be based on aspects such as availability price, logistics of transport, and application of the product. From an environmental point of view, the use of OM fertilizers, as well as PL or any other organic residue, while following technical criteria, may be an important alternative to the correct disposal of organic wastes generated by agriculture and animal production (Borges et al., 2019), as long as manufacturing and logistic costs do not excessively raise the costs of OM fertilizers. Through this mixed fertilizer, regions with a high density of animal production can have an adequate destination for byproducts.

4 | CONCLUSION

Organic, mineral, and OM fertilizers, used in equivalent rates of nutrients, have the same efficiency in the growth and yield of annual agricultural crops. The application of rates of fertilizers higher than the recommended does not result in yield gains of beans, corn, and wheat. In buffering soils with high CEC and moderate to high clay content, fertilizer application increases soil nutrient availability only at the surface layer, close to the deposition of fertilizers in the soil. Fertilization with OM fertilizers and/or PL does not alter the organic carbon content of the soil.

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