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# Comparative impact of organomineral and organic fertilizers as partial substitutes for synthetic fertilizers in enhancing soil fertility, health, and maize growth

## *Impacto comparativo dos fertilizantes organominerais e orgânicos como substitutos parciais dos fertilizantes sintéticos na melhoria da fertilidade do solo, da saúde e do crescimento do milho*

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**ABSTRACT:** Organic and organomineral fertilizers represent sustainable alternatives to conventional mineral fertilization. This study aimed to compare their effects on soil quality indicators and maize performance under greenhouse conditions. Six treatments were evaluated: $T_1$ – mineral fertilization (urea, superphosphate, and potassium chloride); $T_2$ – N & K-supplied organomineral fertilization (dose based on P content); $T_3$ – K-supplied organomineral fertilization (dose based on K content, resulting in excess N and P); $T_4$ – P & K-supplied organic fertilization (dose based on N content); $T_5$ – P-supplied organic fertilization (dose based on P content, resulting in excess N and K); and $T_6$ – mixed fertilization (organomineral + organic). Fertilizers were formulated using residues from swine wastewater and layer manure. The organic fertilizer consisted of a digestate obtained through anaerobic codigestion of the liquid fraction from a mixture of swine wastewater and layer hen manure. The organomineral fertilizer was produced from the solid fraction of these residues, enriched with rock dust and limestone. The study assessed soil fertility, nutrient uptake and translocation, soil respiration, enzyme activity, and microbial biomass. All treatments supported satisfactory plant growth. The highest yield was observed with T5 (P-supplied organic fertilizer), while the lowest was recorded for T6 (mixed fertilization); these two treatments differed significantly from each other, whereas all other treatments showed intermediate values without statistical difference. Enzymatic activities were highest in T3 and T6, both using organomineral fertilizer, indicating greater stimulation of microbial processes and nutrient cycling compared to the other treatments. While the highest yield was obtained with the use of the digestate P-based organic fertilizer (T5), likely due to its similarity to mineral fertilization, organomineral treatments promoted improved soil biological activity, suggesting long-term benefits to soil health. These findings reinforce the potential of organic and organomineral fertilizers to reduce reliance on synthetic inputs while balancing immediate productivity with sustainable soil management.

**KEY WORDS:** Biofertilizer; Digestate; Layer poultry manure; Soil enzymes; Swine wastewater.

**RESUMO:** Fertilizantes orgânicos e organominerais despontam como alternativas sustentáveis à adubação mineral tradicional. Este trabalho avaliou, em casa de vegetação, como essas duas categorias afetam indicadores de qualidade do solo e o desempenho do milho. Seis regimes de adubação foram comparados: ($T_1$) mineral (uréia, superfosfato simples e KCl); ($T_2$) organomineral equilibrado em N e K (dose fixada pelo teor de P); ($T_3$) organomineral balanceado em K (dose definida pelo teor de K, gerando excesso de N e P); ($T_4$) orgânico equilibrado em P e K (dose ajustada pelo teor de N); ($T_5$) orgânico à base de P (dose definida pelo teor de P, com excedentes de N e K); e (T6) adubação mista (organomineral + orgânica). Os insumos derivaram de resíduos de produção animal: o fertilizante orgânico foi um digestato obtido pela codigestão anaeróbia da fração líquida de água residuária da suinocultura e cama de poedeiras, enquanto os organominerais foram produzidos a partir da fração sólida desses mesmos resíduos, enriquecida com pó de rocha e calcário. Analisaram-se fertilidade do solo, absorção e redistribuição de nutrientes, respiração microbiana, atividades enzimáticas e biomassa microbiana. Todos os tratamentos sustentaram crescimento adequado das plantas. O maior rendimento ocorreu no $T_5$, possivelmente pela rápida liberação de nutrientes semelhante à adubação mineral; o menor, no $T_6$. Esses dois tratamentos diferiram estatisticamente, enquanto os demais apresentaram produtividades intermediárias. Por outro lado, as maiores atividades enzimáticas foram registradas nos tratamentos $T_3$ e $T_6$, ambos com organomineral, sinalizando maior estímulo aos microrganismos e à ciclagem de nutrientes. Assim, embora o digestato orgânico baseado em P

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($T_5$) maximize a produtividade de curto prazo, os organominerais demonstram vantagens para a biologia do solo, apontando benefícios em longo prazo. Os resultados reforçam que fertilizantes orgânicos e organominerais podem reduzir a dependência de insumos sintéticos, conciliando ganhos imediatos de produção com um manejo mais sustentável do solo.

**Palavras-chave:** Água residuária da suinocultura; Biofertilizante; Dejetos de galinhas poedeiras; Digestato; Enzimas do solo.

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## 1 INTRODUCTION

For over a century, farmers worldwide have relied on synthetic fertilizers to enrich soils with reduced or fixed forms of minerals essential for crop growth (Kominko *et al.,* 2021; Abebe *et al.,* 2022). However, it is now well established that excessive or improper application of these fertilizers can be ecologically and environmentally detrimental. Such practices negatively impact air, water, and climate, leading to issues like soil acidification, nitrate leaching, erosion, eutrophication, reduced biological diversity, and substantial greenhouse gas emissions, notably nitrous oxide gas 300 times more potent than carbon dioxide ($CO_2$) (Martínez *et al.,* 2021). Despite these well-documented negative effects, the reliance on synthetic fertilizers remains essential to meet the growing global food demand, particularly in developing and emerging countries where usage is on the rise (Martínez *et al.,* 2021; CONAB,2024). For instance, in Brazil, imports of intermediate fertilizers reached 41.34 million tons in 2024, representing a 4.8% increase compared to the same period in 2023. This persistent growth reflects the country's dependence on foreign supply due to insufficient national production to meet agricultural demands (Cruz *et al*., 2017; De Melo Benites *et al*., 2022; ANDA, 2025). In Paraná State of Brazil, the cost to cultivate one hectare of maize is $1819, with $581 (approximately 32% of the total cost) spent directly on fertilizers (OCEPAR,2022). Given this scenario, there is an urgent need for strategies to reduce dependence on synthetic fertilizers.

Farming without synthetic fertilizers is not feasible for most food producers, making the challenge of feeding a rapidly growing world population sustainably a significant one. The most straightforward strategy has been to promote the responsible and efficient use of mineral fertilizers (Abebe *et al.,* 2022). To this end, several framework principles have been developed for all stakeholders involved with fertilizers. Notable among these are the "FAO International Code of Conduct for the Sustainable Use and Management of Fertilizers" and the "4R Nutrient Management Framework" (Martínez *et al.,* 2021). These frameworks offer recommendations for the regulation of fertilizer sales, distribution, and labeling, as well as the production of fertilizers. Such fertilizers improve nutrient use efficiency by enhancing plant uptake and utilization, thereby reducing losses and increasing crop productivity per unit of fertilizer used (FAO, 2019).

Nitrogen (N), phosphorus (P), and potassium (K) are the main nutrients required for plant growth. Synthetic fertilizers, derived from fossil fuels and mined minerals, are commonly used to supply these nutrients but raise concerns about environmental impact and resource dependency (Kominko *et al*., 2021; Abebe *et al*., 2022). Organic and organomineral fertilizers, produced from agro-industrial residues through processes such as anaerobic digestion, offer more sustainable alternatives by recycling nutrients within agricultural systems (Costa *et al*., 2016; Buligon *et al*., 2023; Zilio *et al*., 2023). These inputs contribute to soil health and structure, though their efficiency depends on the quality of raw materials and environmental conditions (Cruz *et al*., 2017; Bouhia *et al*., 2022). Maize, a widely cultivated cereal with high nutrient demand, has shown positive responses to organomineral fertilization in previous studies, particularly when formulations are tailored to crop needs (Fernandes *et al*., 2020; Yıldız; Dizikısa, 2023).

Recently, research has focused on combining the solid portion of digestates with inorganic materials high in nutrients through chemical reactions to produce organomineral formulations (Kominko *et al.,* 2021; Luchese *et al.,* 2023). The European Consortium of the Organic-Based Fertilizer Industry defines organomineral fertilizer as "a complex fertilizer obtained by industrial co-formulation of one or more inorganic fertilizers with one or more organic fertilizers and organic soil improvers into solid forms (except for dry mixtures) or liquids, each unit containing organic carbon and mineral nutrients" (Bouhia *et al.,* 2022). It is hypothesized that organomineral fertilizers are more efficient than mineral fertilizers at high doses due to the higher chemical reactivity and slow-release properties of the organic portion; this results in improved nutrient bioavailability (De Melo Benites *et al.,* 2022). Moreover, organic fertilizers can boost soil biodiversity, enhance fertility by improving both chemical and physicochemical properties, and help preserve the soil's physical structure (Cruz *et al.,* 2017; Bouhia *et al.,* 2022; Costa *et al.,* 2016).

The composition and quality of the organomineral fertilizer formulation are crucial, and in some countries, this composition is now regulated or legislated (Kominko *et al.,* 2021) e.g., in Brazil, Normative Instruction No. 61 of July 8, 2020, issued by the Ministry of Agriculture and Livestock, sets such regulations (MAPA, 2020). Both conventional farming with synthetic chemicals and organic farming with organic amendments have their respective advantages and drawbacks (Abebe *et al.,* 2022; Cruz *et al.,* 2017; Zilio *et al.,* 2022). Consequently, different strategies are required for each type of organic and organomineral fertilizer to optimize their properties and ensure their proper use without compromising the environment and crop production. One promising approach is combining organic and mineral inputs to resolve these issues effectively.

Thus, this study aimed to optimize the composition of organic and mineral fertilizers for maize (*Zea mays* L.) production. Maize plants were grown in soil treated with different fertilization sources: mineral, organomineral, and organic. Various parameters were measured to assess the fertility potential of these products, including plant growth parameters, plant and soil nutritional status, soil enzymatic activities, and microbial activities.

## 2 MATERIALS AND METHODS

### 2.1 SOIL CHARACTERISTICS

The soil used in the experiment was collected from a farm in Cascavel municipality, Brazil (24°57 21 S and 53°27′19″ W), from a depth of 0 to 20 cm. It was characterized as a Red Latosol (Oxisol type). The soil was air-dried, passed through a 4 mm sieve, and homogenized. A composite soil sample was sent to an accredited laboratory (Solanalise Central de Analises Ltd., Cascavel, Brazil) for nutrient content analysis. The chemical characterization of the soil collected: P ($PO_4^{3-}$) = 13.2 mg $kg^{-1}$; K = 425 mg $kg^{-1}$; Ca = 9.14 cmolc $kg^{-1}$; Mg = 3.55 cmolc $kg^{-1}$; S= 6.24 mg $kg^{-1}$; B = 0.38 mg $kg^{-1}$; Fe = 11.8 gm $kg^{-1}$; Mn = 30.8 mg $kg^{-1}$; Cu = 3.20 mg $kg^{-1}$; Zn = 2.20 mg $kg^{-1}$; Organic matter content (SOM) = 38.2 g $kg^{-1}$; Total organic carbon (TOC) = 22.2 g $kg^{-1}$. pH = 5.3.

#### 2.1.1 Preparation of fertilizers

Mineral (synthetic) fertilizers were obtained from local suppliers. Urea with 45% N content was used as the N source, superphosphate simple with 18% $P_2O_5$ content was used as the P source, and potassium chloride with 60% $K_2O$ content was used as the K source.

The organic fertilizer was a digestate obtained through the anaerobic digestion of a mixture of liquid swine wastewater and laying hen manure from an animal farm in Paraná. Briefly, the mixture was processed in a horizontal tubular biodigester with a 1.014 $m^3$ capacity (Buligon *et al.,* 2023). Digestion occurred in a semi-continuous system with a hydraulic retention time of 20 days and a mesophilic-controlled temperature of 35 °C. Chemical characterization of the digestate by an accredited laboratory revealed the following nutrient levels: N = 4.20 g $L^{-1}$; $P_2O_5$ = 0.20 g $L^{-1}$; $K_2O$ = 1.90 g $L^{-1}$; Ca = 181 mg $L^{-1}$; Mg = 80.6 mg $L^{-1}$; S = 0.20 mg $L^{-1}$; B = 0.10 mg $L^{-1}$; Fe = 13.5 mg $L^{-1}$; Mn = 3.00 mg $L^{-1}$; Cu = 6.30 mg $L^{-1}$; and Zn = 6.60 mg $L^{-1}$.

The organomineral fertilizer consisted of a mixture by weight of 40% solid fraction of swine wastewater, 30% laying hen manure, 15% rock dust, and 15% calcitic limestone. Certified rock dust and calcitic limestone in fine powder form were obtained from a local provider. The rock dust was mined from volcanic basalt rock and, according to the manufacturer, contained prominent minerals such as $SiO_2$ (51.3%), $Fe_2O_3$ (15.7%), Al O (12.3%), CaO (8.6%), MgO (4.6%), $K_2O$ (1.2%), $Na_2O$ (2.7%), $TiO_2$ (2.3%), MnO (0.23%), and $P_2O_5$ (0.29%). These contents were similar to those reported by Luchese *et al*., (2023). The calcitic limestone consisted of 45% CaO, 4% MgO, and 72.5% effective $CaCO_3$ equivalent. The organomineral fertilizer was produced at a local biogas facility. Initially, a mixture of swine wastewater and laying hen manure was homogenized in a tank for digestion. The biogas generated was captured through a gas pipeline, while the solid fraction of the digestate was separated from the liquid and transferred to another tank. Rock dust and limestone were then incorporated into the solid fraction. The resulting mixture was dried using biogas as the fuel source, cooled at room temperature, sieved, and then packaged. The resulting organomineral product had the following composition: N = 13.4 g $kg^{-1}$; P ($PO_4^{3-}$) = 6.80 g $kg^{-1}$; K = 1.30 g $kg^{-1}$; Ca = 173 mg $kg^{-1}$; Mg = 12.7 mg $kg^{-1}$; S = 9.30 mg $kg^{-1}$; B = 0.30 mg $kg^{-1}$; Fe = 11.7 mg $kg^{-1}$; Mn = 0.43 mg $kg^{-1}$; Cu = 0.15 mg $kg^{-1}$; and Zn = 0.23 mg $kg^{-1}$.

### 2.1.2 Fertilization treatments

Six treatments were established based on the soil's chemical composition, with fertilizer amounts determined according to recommendations from the Fertilization and Liming Manual for the State of Paraná, Brazil (Pavinato *et al.,* 2017). Application rates per hectare were calculated aiming for 300 kg of N, 120 kg of $P_2O_5$, and 115 kg of $K_2O$.

Each treatment used specific fertilizer sources: T1 = mineral (synthetic) fertilization, using urea for N, superphosphate simple for $P_2O_5$, and potassium chloride for $K_2O$; T2 = N & K-supplied organomineral fertilization, with the dose based on the highest macronutrient content in the organomineral product, P; additional N and K were supplied using urea and potassium chloride, respectively; T3 = K-supplied organomineral fertilization, with the dose based on the lowest macronutrient content in the organomineral product, K; this resulted in excess N and P; T4 = P & K-supplied organic fertilization, with the dose based on the highest macronutrient content in the digestate, N; additional P and K were provided using superphosphate simple and potassium chloride, respectively; T5 = P-supplied organic fertilization, with the dose based on the lowest macronutrient content in the digestate, P; this led to excess N and K; T6 = mixed fertilization, combining K-supplied organomineral fertilizer with the organic fertilizer (digestate). Fertilizers were applied at different growth stages of maize based on the crop's specific needs as described below.

## 2.2 GREENHOUSE EXPERIMENT

The soil was distributed into 20-L plastic pots with dimensions of 31 cm in height, a top diameter of 31 cm, a bottom diameter of 27 cm, and four drainage holes. Each pot was filled to three-quarters of its height (25 cm) and transported to a plastic greenhouse measuring 8 m in width and 10 m in length. This greenhouse is located at Universidade Estadual do Oeste do Paraná (Cascavel, Brazil) and operates under natural temperature and light conditions.

The soil in each pot was irrigated with tap water and maintained at 70% of its water-holding capacity throughout the study by adding water to the prescribed weight on alternate days. The pots were arranged on the greenhouse floor in a completely randomized block design, with four replicates per treatment. The pots were spaced 20 cm apart, and blocks were placed at least 2 m apart in different areas of the greenhouse to account for variations in internal environmental conditions. Two seeds of the hybrid maize cultivar B2688P-WU-Brevant (Corteva Agriscience, Barueri, Brazil) were sown at a depth of 2.5 cm in the middle of each pot. Ten days after emergence, when the seedlings reached the two-leaf stage, thinning was performed to leave one plant per pot. The plants were grown from October to February with temperatures ranging from 17.9–20.7 °C at night and 30.0–32.1 °C during the day, 75% relative humidity, and a 9-hour photoperiod. No pest control measures were implemented, and pots were frequently weeded by hand as necessary.

Except for the sixth treatment, fertilizers in all treatments were split-applied. Initially, 50 kg of N, 60 kg of $P_2O_5$, and 60 kg of $K_2O$ were applied as a basal dose 4 days after plant emergence. The remaining 250 kg of N, 60 kg of $P_2O_5$, and 55 kg of $K_2O$ were applied as a top-dressing 28 days after plant emergence. For the mixed fertilization treatment, 70 kg of N, 80 kg of $P_2O_5$, and 40 kg of $K_2O$ were applied as a basal dose using the K-supplied organomineral fertilizer. The remaining 230 kg of N, 40 kg of $P_2O_5$, and 75 kg of $K_2O$ were applied as a top-dressing using the digestate as organic fertilization. Fertilizers were thoroughly mixed with the top 10 cm of soil in the pots using a small garden spade.

## 2.3 SOIL AND PLANT MEASUREMENTS

### 2.3.1 Leaf biochemical analyses

When maize reached the dough stage (R4), the third leaf, counted from the base and below the upper ear, was cut using a knife. The leaf was gently washed with distilled water and incubated in a forced air circulation oven at 40°C for 24 h. After drying, leaf veins and midribs were removed, and the remaining leaf material was ground to pass through a 2-mm screen using a Micro Wiley Mill (Tecnal, Piracicaba, Brazil). All chemicals used for the analyses were sourced from Química Moderna (Barueri, São Paulo, Brazil). The contents of P and K were determined by digesting the samples in a nitric-perchloric acid solution (3:1) with an external heat source, followed by dilution and filtration. P was detected by measuring absorbance at 725 nm using a DR6000 UV-VIS spectrophotometer (Hach, Loveland, CO). K was quantified using a DM-62 flame photometer (Digimed, Campo Grande, Brazil) (Qi *et al.,* 2016). The same nitric-perchloric acid mixture (3:1) was used to extract Zn, Fe, Cu, Mn, Mg, and Ca, with these elements determined using atomic absorption spectroscopy (Shimadzu AA6300, Tokyo, Japan) (Silva, 2009). Nitrogen (N) content in the leaves was determined using the Kjeldahl method, which involves digesting the samples with a mixture of 100 g Na SO , 10 g $CuSO_4$, and 1 g Se. The sample was then titrated using 0.1 N H SO (Silva, 2009).

### 2.3.2 Crop growth attributes

During plant growth, the following phytometric parameters were measured weekly: stem diameter (mm), plant height (cm), and leaf area ($cm^2$). The stem diameter was measured 1 cm above the soil level using a digital caliper. Plant height was recorded as the distance from the base of the plant to the tip of the last fully opened leaf, using graduated tape. Leaf length and width were also measured with a graduated tape, and leaf area was calculated using the equation: Leaf Area ($cm^2$) = 0.7458 × Leaf Width (cm) × Leaf Length (cm) (Guimarães,2002).

At the full-grain maturity stage (after R6), the ears were manually harvested, dehusked, and threshed to collect the grains. The moisture content was determined to be, on average, 25%. Maize yield immediately after harvest was estimated using the equation: Field Yield = Grain Weight (g) × Plant Population (per $ha^{-1}$). Moisture correction was applied using the equation: Yield = Field Yield × [(100 – Field Humidity) / (100 – Desired Humidity)], with the desired humidity set at 13%.

Plants were uprooted, and the roots were cut off and rinsed with running tap water. The roots were then dried at 105°C in an oven with forced air circulation to determine the root dry matter (DM) using a semi-analytical balance.

Soil physicochemical analyses

In each pot, three soil cores were randomly collected at harvest (90 days after fertilization) from the top 10 cm using a garden spade. These cores were combined and sieved (2 mm) to create a composite sample. Soil pH was measured by the potentiometric method with water, and electrical conductivity (EC) was determined using a probe on a benchtop conductivity meter (Teixeira *et al.,* 2017). Exchangeable Ca and Mg were extracted with 1 M KCl and determined using an AA-6300 Atomic Absorption Spectrophotometer (Shimadzu Corporation, Kyoto, Japan). Available P was extracted with a Mehlich$^{-1}$ extract and analyzed at 660 nm using a DR6000 UV-VIS spectrophotometer (Hach, Loveland, CO). Exchangeable K in the Mehlich-1 extract was determined with a DM-62 flame photometer (Digimed, Campo Grande, Brazil), while Zn, Cu, Mn, and Fe were determined with an Atomic Absorption Spectrophotometer. After sample digestion with 1:1 HCl, S was precipitated with $BaCl_2$ and determined gravimetrically (Teixeira *et al.,* 2017). B was extracted using the hot-water-$BaCl_2$ method and measured at 420 nm (Silva,2009). Total organic carbon (TOC) was determined based on the Walkley e Black chromic acid wet oxidation method (Walkley; Black, 1934). Soil organic matter (SOM) was measured using the loss-on-ignition gravimetric method in a muffle furnace at 550 °C, without the addition of $FeCl_2$ (Hoogsteen *et al.,* 2018). All results are presented on a dry weight basis.

### 2.3.3 Soil biochemical analyses

For soil biochemical analyses, the collected soil was immediately frozen at -20°C and kept until analysis. The enzymatic activities of urease, phosphatase, and arylsulfatase were determined following Tabatabai (1994). Urease activity was measured using the steam distillation method; the $NH_4^+$ released was quantified using MgO, based on Mulvaney (1996), with urease activity expressed in mg $NH_4^+$ $kg^{-1}$ $h^{-1}$. The activities of acid and alkaline phosphatases were determined using the p-nitrophenyl phosphate assay at 400 nm, with results expressed as $\mu$mol of p-nitrophenol $g^{-1}$ $h^{-1}$. Arylsulfatase activity was determined using the same principle as the phosphatase method but replacing p-nitrophenyl phosphate with p-nitrophenyl sulfate.

The microbial biomass carbon (MBC) of the soil was determined using the fumigation-extraction method described in Silva *et al.* (2007), with the conversion factor for carbon to microbial biomass being 0.33 and expressed in mg C $kg^{-1}$. Basal soil respiration (BSR) was measured by quantifying $CO_2$ released after 48 h of soil incubation under aerobic conditions in closed jars and expressed as $\mu$g CO2 $g^{-1}$ $h^{-1}$ (Alef, 1995). The metabolic quotient ($qCO_2$) was calculated as the ratio between BSR and MBC and expressed as $\mu$g $CO_2$ $\mu$g $C^{-1}$ $h^{-1}$ (Silva *et al.,* 2007).

Soil fungal biomass was assessed following the method of Bloem and Vos (2004). Microorganisms in a homogenized soil suspension were stained with the fluorescent dye calcofluor white. The intersection grid method was employed, randomly selecting 100 fields to determine the presence or absence of fungal hyphae. Hyphae length was estimated using a Nikon D-FL epifluorescence microscopy (Boston, USA) under blue illumination at 400x magnification. The total hyphae length (m $g^{-1}$ soil) was calculated to estimate fungal biomass. For bacterial biomass determination, a soil smear was prepared on a slide and stained with 5-(4,6-dichlorotriazine-2-yl) aminofluorescein. The bacterial biovolume was estimated using epifluorescence microscopy under blue illumination at 1000x magnification, with 10 randomly selected fields of view within an ocular grid. Bacterial biomass data are reported as mg $g^{-1}$ soil (Bloem e Vos,2004).

### 2.3.4 Statistical analyses

Statistical analyses were performed using the software Sisvar 5.6-Build 86. Bartlett, Levene, and Shapiro-Wilk tests were conducted to confirm that the data met the homoscedasticity, homogeneity of variance, and normal distribution criteria, respectively. The data were subjected to Analysis of Variance, and means were compared using Tukey's HSD test at a 5% probability level. Data are reported as mean ± standard deviation. The coefficient of variance is also reported as a measure of the dispersion of data points around the mean, independent of parameters' units. A Principal Component Analysis (PCA) employing soil biochemical data was conducted to discern the mode of action of the fertilizers more accurately; the outcome of this comprehensive multivariate exploratory analysis was visually represented using a Biplot graph.

## 3 RESULTS AND DISCUSSION

### 3.1 MAIZE PRODUCTIVITY

Compared to mineral fertilization, the other fertilization treatments did not affect plant height, leaf area, or root DM (Table 1). Minor statistical differences ($P < 0.05$) were observed for stem diameter and grain yield. Maize plants grown on soil fertilized with K-supplied organominerals and the mixed product exhibited the largest stem diameter (23.8 mm and 22.8 mm, respectively), which was similar to the other maize plants but higher than those grown on soil fertilized with NK-supplied organominerals (19.4 mm). The P-supplied organic fertilizer resulted in the highest grain yield of 9.41 t $ha^{-1}$. Although not statistically different, the P-supplied organic fertilizer increased grain yield by 13.4% compared to mineral fertilizer, equivalent to an additional 19 sacks of maize per ha. Although the lowest numerical grain yield (6.48 t $ha^{-1}$) was observed under the mixed products treatment, it was statistically lower only in comparison to the Organic-supplied-P treatment (9.41 t $ha^{-1}$), which achieved the highest yield (Table 1).

**Table 1.** Effect of different fertilizer types on phytometric parameters and maize yield

| Fertilizer type | Plant height (cm) | Leaf area ($cm^2$) | Root DM (g) | Stem diameter (mm) | Grain yield (t $ha^{-1}$) |
|---|---|---|---|---|---|
| Mineral (synthetic) | 105 ± 3.55 $^{a}$ | 506 ± 21.7 $^{a}$ | 39.3 ± 9.56 $^{a}$ | 21.5 ± 1.41 $^{ab}$ | 8.30 ± 0.49 $^{ab}$ |
| Organomineral-NK | 104 ± 4.72 $^{a}$ | 417 ± 57.1 $^{a}$ | 41.7 ± 9.30 $^{a}$ | 19.4 ± 0.73 $^{b}$ | 8.49 ± 0.99 $^{ab}$ |
| Organomineral-K | 109 ± 6.16 $^{a}$ | 539 ± 70.3 $^{a}$ | 36.9 ± 7.27 $^{a}$ | 23.8 ± 2.12 $^{a}$ | 7.88 ± 0.50 $^{ab}$ |
| Organic-supplied-PK | 100 ± 8.50 $^{a}$ | 480 ± 71.1 $^{a}$ | 49.5 ± 12.2 $^{a}$ | 20.0 ± 1.34 $^{ab}$ | 8.35 ± 0.74 $^{ab}$ |
| Organic-supplied-P | 105 ± 3.53 $^{a}$ | 475 ± 24.2 $^{a}$ | 40.5 ± 5.66 $^{a}$ | 21.2 ± 1.20 $^{ab}$ | 9.41 ± 0.89 $^{a}$ |
| Mixed products | 101 ± 1.33 $^{a}$ | 428 ± 24.6 $^{a}$ | 39.9 ± 9.84 $^{a}$ | 22.8 ± 1.68 $^{a}$ | 6.48 ± 0.46 $^{b}$ |
| CV (%) | 5.60 | 12.1 | 24.4 | 7.81 | 12.5 |

Phytometric data were collected at V7, while yield was estimated after R6. The mixed fertilizer consisted of the K-supplied organominerals applied at planting and the digestate applied as topdressing. The other treatments were split-applied as described in the "Methods" section. Within each column, means ± SD followed by the same letter do not differ from each other based on Tukey's HSD test at a 5% probability level. CV indicates coefficient of variance.

In the present study, fertilizing maize at two growth stages with the same product—whether mineral, organomineral, or organic fertilizer—generally resulted in comparable grain yields, with few statistically significant differences among treatments. The highest yield (9.41 t $ha^{-1}$) was achieved with the P-supplied organic fertilizer, derived from a digestate of swine wastewater and layer manure; this formulation was carefully balanced to address the macronutrient with the lowest concentration in the digestate (P), resulting in an excess of N and K. In contrast, the only treatment with significantly lower yield was the mixed fertilization (K-supplied organomineral at planting and digestate at topdressing), which produced 6.48 t $ha^{-1}$, statistically lower only when compared to the P-supplied organic fertilizer. Other treatments showed no statistical differences from each other, despite numerical variation (Table 1).

In a technical report from EMBRAPA, Nicoloso *et al*. (2024) concluded that, when applying the same fertilization practices, liquid swine manure stored in holding ponds and swine manure treated through anaerobic digestion exhibit agronomic efficiency levels similar to those of mineral fertilizers, such as urea. Therefore, they can be used as nitrogen sources for agricultural crops, with fertilization recommendations based on 100% availability of their total nitrogen content. An interesting finding was that organomineral fertilizers composed of raw swine wastewater and layer manure showed similar nutrient efficiency for maize compared to the processed digestate from the same raw materials.

### 3.1.1 Leaf diagnosis

Except for Cu and Mn, which exceeded the typical maximum levels, nutrient levels in the leaves fell within the expected range for the study region, suggesting the fertilizers did not exert a toxic effect on maize plants (Table 2). Throughout the experiment, no toxicity symptoms were observed. Compared to mineral fertilization, leaf levels of P, Ca, Mg, Zn, and Mn remained unaffected by the various fertilizer treatments. Similar to grain yield, the highest N contents were observed with P-supplied organic fertilizer (32.4 g $kg^{-1}$) and organomineral-NK (31.3 g $kg^{-1}$), with no significant difference between them. In contrast, the lowest values were found under K-supplied organomineral (22.1 g $kg^{-1}$) and the mixed product treatment (24.5 g $kg^{-1}$). The lowest K content (19.0 g $kg^{-1}$) was observed with the K-supplied organomineral fertilizer, and it was significantly lower than the value observed with the mineral treatment (33.2 g $kg^{-1}$). The mixed fertilization also resulted in lower K levels (25.2 g $kg^{-1}$), although not significantly different from most other treatments (Table 2). Maize cultivated with mineral fertilizers consistently exhibited optimal nutrient levels in the leaves, particularly K (33.2 g $kg^{-1}$) and Cu (84.6 mg $kg^{-1}$).

Treatments that resulted in higher nitrogen availability reflected by elevated N concentrations in the leaves also supported increased maize yields (Table 2), indicating that improved nitrogen uptake played a key role in promoting plant growth and productivity (Jahromi *et al.,* 2020; De Melo Benites *et al.,* 2022). This increase in yield was attributed to higher available N content in the digestate-based organic fertilizer, facilitating maximum total N assimilation. Anaerobic digestion, employed to produce the digestate, offers distinct advantages over other waste processing methods such as composting, vermicomposting, and static windrows.

**Table 2.** Leaf nutrient levels of maize grown with fertilizers from different sources

| Fertilizer type | N | P | K | Ca | Mg | Cu | Zn | Fe | Mn |
|---|---|---|---|---|---|---|---|---|---|
| | -------------------- | g $kg^{-1}$ | -------------------- | | | --- mg $kg^{-1}$ --- | | --- $\mu$g $kg^{-1}$ --- | |
| Mineral (synthetic) | 28.3±2.91[b] | 1.70±0.41[a] | 33.2±3.30[a] | 3.21±0.34[a] | 12.6±0.40[a] | 84.6±0.57[a] | 91.2±0.14[a] | 0.19±0.01[a] | 1.40±0.16[a] |
| Organomineral-NK | 31.3±4.48[a] | 1.82±0.76[a] | 26.7±3.00[ab] | 3.26±0.29[a] | 11.2±0.58[a] | 73.7±0.99[ab] | 82.9±0.67[a] | 0.19±0.01[a] | 1.47±0.25[a] |
| Organomineral-K | 22.1±2.74[c] | 1.86±0.14[a] | 19.0±2.58[c] | 3.18±0.50[a] | 11.4±1.14[a] | 61.3±0.18[bc] | 84.8±0.88[a] | 0.20±0.01[a] | 1.42±0.20[a] |
| Organic-supplied-PK | 28.3±3.62[b] | 1.58±0.40[a] | 23.7±2.62[bc] | 3.45±0.33[a] | 12.8±0.91[a] | 64.0±0.53[bc] | 81.1±1.07[a] | 0.22±0.01[a] | 1.53±0.18[a] |
| Organic-supplied-P | 32.4±1.25[a] | 1.75±0.39[a] | 23.8±1.37[bc] | 3.90±0.57[a] | 11.9±0.65[a] | 59.0±0.44[c] | 85.7±0.99[a] | 0.21±0.01[a] | 1.50±0.17[a] |
| Mixed products | 24.5±2.11[bc] | 1.60±0.35[a] | 25.2±2.84[bc] | 3.00±0.35[a] | 13.0±1.55[a] | 31.9±0.08[d] | 94.2±0.08[a] | 0.11±0.01[b] | 1.39±0.26[a] |
| CV (%) | 12.0 | 12.1 | 12.3 | 10.7 | 8.60 | 9.84 | 12.3 | 13.8 | 16.9 |
| Reference levels | 27.5-35.0 | 1.90-4.00 | 17.0-35.0 | 2.30-8.00 | 1.50-15.0 | 6.00-20.0 | 30.0-250 | 0.02-0.20 | 0.01-0.10 |

Leaves were sampled at the R4 growth stage. The mixed fertilizer consisted of the K-supplied organominerals applied at planting and the digestate applied as topdressing. The other treatments were split-applied as described in the "Methods" section. Within each column, means ± SD followed by the same letter do not differ from each other based on Tukey's HSD test at a 5% probability level. CV indicates coefficient of variance. Reference levels correspond to maize grown in Paraná, Brazil (Pavinato *et al.,* 2017).

Notably, it converts organic N into $NH_4^+$, and being an in-vessel process, it enhances nutrient retention (Costa *et al.,* 2016; Martínez-Dalmau *et al.,* 2021). Consequently, digestates from anaerobic digestion are valuable sources of readily available nutrients for plants, particularly N and K. Furthermore, it is plausible that during mineralization and nitrification, heterotrophic microorganisms efficiently converted organic N into inorganic forms ($NH_4^+$ and $NO_3^-$), as indicated by the low urease activity observed at harvest in soils treated with P-supplied organic fertilizer (Table 5).

The treatments with the lowest yields (mixed fertilizer and K-supplied organomineral fertilizer) tended to exhibit lower levels of N in the leaves but larger stem diameter (Table 1; Table 2). The K-supplied organomineral fertilizer was formulated based on the deficiency of K in the original organomineral mixture, resulting in an excess of N and P. This surplus may have been utilized more for stem growth at the expense of leaf growth or grain formation. It is also possible that some excess N might have been lost through ammonia volatilization, as the combination of organic fertilizers and minerals reduced the soil's nitrogen fixation capacity through adsorption and precipitation mechanisms, thereby enhancing its extractability (Coelho,2006). According to Gonzatto *et al*. (2013) approximately 80% of N losses through $NH_3$ volatilization occur within the first 22 h after application of liquid swine manure to the soil.

Alternatively, the excess N might have required more time for mineralization by soil microbiota and subsequent release to become fully accessible to plants; according to Costa *et al*. (2016) 60% of N in digestates exists as $NH_4^+$ i.e., the excess N is primarily in organic form. In the case of mixed fertilization treatment, the digestate applied during topdressing may not have been timely or early enough to compensate for N loss through ammonia volatilization. Furthermore, urease, phosphatase, and arylsulfatase activities in treatments without supplemental N in the form of urea (K-supplied organomineral fertilizer and mixed fertilizer) were the highest compared to other treatments (Table 5). Elevated enzyme activities indicate rapid ammonia formation, which, if not absorbed by soil colloids, can volatilize (Qi *et al.,* 2016)

### 3.1.2 Soil physiochemistry

The different fertilizer sources contributed to an increase in soil pH (average 6.5), compared to the initial pH value of 5.3 at the beginning of the experiment, which is consistent with findings from several studies (De Melo Benites *et al.,* 2022; Jahromi *et al.,* 2020). The highest pH increase (6.6) was observed after mixed fertilization. Additionally, mixed fertilization resulted in the highest levels of TOC (17.7 g $kg^{-1}$) and SOM (30.6 g $kg^{-1}$) compared to the other treatments. On average, TOC and SOM levels in fertilized soil were 37% (from 22.2 to 13.9 g $kg^{-1}$) and 15% (from 28.2 to 24.0 g $kg^{-1}$) lower than in non-fertilized soil, respectively (Table 3). In contrast, the lowest EC value (56.2 $\mu$S $cm^{-1}$) was recorded in soil treated with mixed fertilization, while the highest EC was found in soil fertilized with K-supplied organominerals (190 $\mu$S $cm^{-1}$).

Soil physicochemical analyses revealed distinct patterns among treatments. At harvest, soils under mixed fertilization showed the highest numerical levels of TOC and SOM. However, these values were statistically similar to those observed with P-supplied organic fertilizer and organomineral-NK, indicating that multiple treatments contributed comparably to the increase in soil organic matter content (Table 3). This may be attributed to the addition of both organomineral and organic inputs, which potentially increased carbon input, even though the availability to plants appears limited. As described by Bouhia *et al*. (2022), increases in SOM contribute to improved soil structure, nutrient retention, and microbial habitat. However, the expected agronomic benefit may not have been fully realized, as TOC alone does not guarantee effective nutrient release or plant uptake.

**Table 3.** Physicochemical characteristics and levels of primary macronutrients in soil treated with fertilizers of different sources

| Fertilizer type | pH ($CaCl_2$) | EC ($\mu$S $cm^{-1}$) | TOC (g $kg^{-1}$) | SOM (g $kg^{-1}$) | P (mg $kg^{-1}$) | K (mg $kg^{-1}$) |
|---|---|---|---|---|---|---|
| Mineral (synthetic) | 6.4±0.1$^{b}$ | 57.0±6.55$^{b}$ | 12.6±1.15$^{b}$ | 21.7±1.96$^{b}$ | 22.2±2.90$^{a}$ | 124±28.1$^{b}$ |
| Organomineral-NK | 6.5±0.1$^{ab}$ | 62.2±17.4$^{b}$ | 13.9±1.57$^{ab}$ | 24.0±2.63$^{ab}$ | 21.9±2.83$^{a}$ | 113±13.8$^{b}$ |
| Organomineral-K | 6.5±0.1$^{ab}$ | 190 ±43.3$^{a}$ | 12.3±2.20$^{b}$ | 21.1±3.91$^{b}$ | 21.3±2.00$^{a}$ | 206±16.2$^{a}$ |
| Organic-supplied-PK | 6.4±0.0$^{b}$ | 73.0±24.2$^{b}$ | 13.5±3.63$^{b}$ | 23.2±6.38$^{b}$ | 21.2±3.91$^{a}$ | 185±65.6$^{a}$ |
| Organic-supplied-P | 6.4±0.0$^{b}$ | 68.2±7.40$^{b}$ | 13.6±3.35$^{ab}$ | 23.4±5.60$^{ab}$ | 20.2±1.64$^{a}$ | 224±39.6$^{a}$ |
| Mixed products | 6.6±0.2$^{a}$ | 56.2±8.92$^{b}$ | 17.7±3.20$^{a}$ | 30.6±5.52$^{a}$ | 19.5±1.24$^{a}$ | 136±18.8$^{b}$ |
| CV (%) | 1.62 | 28.0 | 20.4 | 20.4 | 13.1 | 18.9 |
| Initial nonfertilized | 5.3 | NA | 22.2 | 38.2 | 13.2 | 425 |

The mixed fertilizer consisted of the K-supplied organominerals applied at planting and the digestate applied as topdressing. The other treatments were split-applied as described in the "Methods" section. Within each column, means ± SD followed by the same letter do not differ from each other based on Tukey's HSD test at a 5% probability level. CV indicates coefficient of variance. EC = Electrical conductivity; TOC = Total Organic Carbon; SOM = Soil Organic Matter. NA = not analyzed.

In terms of electrical conductivity (EC), the mixed treatment (T6) showed intermediate values (56.2 $\mu$S $cm^{-1}$), statistically similar to most other treatments, but significantly lower than the K-supplied organomineral treatment (T3), which reached 190 $\mu$S $cm^{-1}$—the highest EC observed. This suggests that although mixed fertilization promoted higher soil organic matter content, it did not increase the concentration of soluble ions in the short term. In contrast, the elevated EC in T3 indicates greater immediate availability of mineral nutrients, likely due to the excess input of N and P relative to K.

No significant differences in pH were observed among most treatments, but T6 showed the highest mean pH (6.6) when compared to T1, T4 and T5, possibly due to the buffering effect of the combined application of digestate and rock-based inputs. Regarding phosphorus (P), no significant differences were observed among treatments, indicating that the source and form of fertilization did not markedly alter P availability in the soil under the conditions of this study.

Potassium levels in the soil differed significantly among treatments (Table 3). The highest concentrations were observed in T5 (224 mg kg$^{-1}$), T3 (206 mg kg$^{-1}$), and T4 (185 mg kg$^{-1}$), all of which received substantial K inputs—either through targeted supplementation (T4), dosage based on K content (T3), or surplus application relative to other nutrients (T5). These treatments were statistically superior to T1, T2, and T6, which exhibited lower soil K levels (124, 113, and 136 mg kg$^{-1}$, respectively). These results underscore the importance of proper K balancing in fertilization strategies, especially for K-demanding crops like maize.

The high K content in T5, which was dosed based on P (the limiting nutrient in the digestate), suggests that excessive K inputs can result when formulations are not proportionally adjusted. On the other hand, the elevated K level in T3 reflects the deliberate compensation for the lowest nutrient concentration in the organomineral product. Despite the different origins and application strategies, the treatments with higher K input were more effective in maintaining soil K availability post-harvest. These results reinforce the role of potassium management not only in immediate nutrient availability but also in ensuring soil fertility continuity across cropping cycles.

### 3.1.3 Soil nutrients

At the conclusion of the experiment, soil samples were collected and analyzed to compare nutrient levels with those measured in the unfertilized soil at the beginning of the experiment (Table 3; Table 4).

**Table 4.** Levels of secondary macronutrients and micronutrients in soil treated with fertilizers of different sources

| Fertilizer type | S | Ca | Mg | Cu | Fe | Zn | Mn | B |
|---|---|---|---|---|---|---|---|---|
| | ------ cmol$_c$ kg$^{-1}$ ------ | | | ------------------ mg kg$^{-1}$ ------------------ | | | | |
| Mineral (synthetic) | 4.17±0.52$^{b}$ | 55.4±0.76$^{b}$ | 3.41±0.05$^{a}$ | 0.72±0.21$^{b}$ | 4.53±1.30$^{ab}$ | 2.29±1.10$^{a}$ | 0.51±0.39$^{a}$ | 0.62±0.27$^{a}$ |
| Organomineral-NK | 3.11±0.45$^{bc}$ | 56.1±0.72$^{ab}$ | 3.40±0.11$^{a}$ | 0.55±0.08$^{b}$ | 3.70±0.42$^{ab}$ | 0.84±0.30$^{b}$ | 0.32±0.10$^{ab}$ | 0.56±0.20$^{a}$ |
| Organomineral-K | 10.4±1.20$^{a}$ | 57.7±1.77$^{ab}$ | 3.62±0.45$^{a}$ | 0.90±0.07$^{a}$ | 2.70±0.45$^{b}$ | 0.57±0.33$^{b}$ | 0.32±0.18$^{ab}$ | 0.51±0.04$^{a}$ |
| Organic-supplied-PK | 2.96±0.30$^{bc}$ | 57.3±0.51$^{ab}$ | 3.17±0.01$^{a}$ | 0.92±0.06$^{a}$ | 5.25±0.90$^{a}$ | 0.31±0.22$^{b}$ | 0.28±0.07$^{ab}$ | 0.64±0.10$^{a}$ |
| Organic-supplied-P | 2.53±0.10$^{c}$ | 57.0±1.00$^{ab}$ | 3.15±0.50$^{a}$ | 0.23±0.02$^{c}$ | 3.86±0.59$^{ab}$ | 0.66±0.45$^{b}$ | 0.26±0.13$^{ab}$ | 0.57±0.07$^{a}$ |
| Mixed products | 3.00±0.57$^{bc}$ | 58.2±1.25$^{a}$ | 3.36±0.03$^{a}$ | 0.18±0.03$^{c}$ | 4.02±1.76$^{ab}$ | 2.90±1.57$^{a}$ | 0.10±0.02$^{b}$ | 0.53±0.28$^{a}$ |
| CV (%) | 16.2 | 2.20 | 9.04 | 14.6 | 26.0 | 31.3 | 33.6 | 14.5 |
| Initial nonfertilized | 6.24 | 9.14 | 3.55 | 3.20 | 11.8 | 2.20 | 30.8 | 0.38 |

The mixed fertilizer consisted of the K-supplied organominerals applied at planting and the digestate applied as topdressing. The other treatments were split-applied as described in the “Methods” section. Within each column, means ± SD followed by the same letter do not differ from each other based on Tukey’s HSD test at a 5% probability level. CV indicates coefficient of variance.

Across all evaluated conditions, there was an increase in soil levels of P (62%), Ca (523%), B (50%). Conversely, K, Cu, Fe, and Mn levels decreased by 61%, 82%, 66%, and 99%, respectively. Levels of S, Mg, and Zn remained relatively stable. No differences were observed among fertilization treatments for P, Mg, and B; for the remaining nutrients, no consistent trends were evident in the data (Table 3; Table 4).

### 3.1.4 Soil enzymes

The highest levels of soil organic matter (SOM) and total organic carbon (TOC) were observed in the mixed fertilization treatment (T6) (Table 5), which also showed statistically higher arylsulfatase activity

(7.36 μmol pNS $g^{-1}$ $h^{-1}$) compared to all other treatments. This suggests that the increased organic matter in this treatment provided more substrate and favorable conditions for microbial groups involved in sulfur cycling. For urease activity, both T3 (Organomineral-K) and T6 exhibited the highest values, statistically superior to the mineral and Organomineral-NK treatments, indicating enhanced nitrogen transformation capacity. Acid and alkaline phosphatase activities were also significantly higher in T3, followed by T6 and T4, suggesting improved phosphorus mineralization potential in treatments receiving greater organic inputs.

**Table 5.** Activities of enzymes in soil treated with fertilizers of different sources

| Fertilizer type | Urease ($NH_4^+$ mg $kg^{-1}$ $h^{-1}$) | Acid phosphatase (μmol pnp $g^{-1}$ $h^{-1}$) | Alkaline phosphatase (μmol pnp $g^{-1}$ $h^{-1}$) | Arylsulfatase (μmol pns $g^{-1}$ $h^{-1}$) |
|---|---|---|---|---|
| Mineral (synthetic) | 178 ± 18.3 b | 41.4 ± 17.8 d | 47.2 ± 15.9 c | 5.01 ± 1.04 b |
| Organomineral-NK | 179 ± 13.1 b | 87.4 ± 21.2 bc | 81.9 ± 10.4 bc | 3.99 ± 0.57 b |
| Organomineral-K | 222 ± 30.9 a | 162 ± 10.3 a | 153 ± 31.6 a | 6.00 ± 1.35 b |
| Organic-supplied-PK | 178 ± 9.30 b | 95.8 ± 11.4 bc | 104 ± 6.5 ab | 4.72 ± 0.70 b |
| Organic-supplied-P | 208 ± 29.6 ab | 73.3 ± 15.0 c | 78.2 ± 9.1 bc | 4.58 ± 0.43 b |
| Mixed products | 229 ± 35.8 a | 135 ± 41.2 ab | 108 ± 11.9 ab | 7.36 ± 0.76 a |
| CV (%) | 13.3 | 25.7 | 19.9 | 19.6 |

The mixed fertilizer consisted of the K-supplied organominerals applied at planting and the digestate applied as topdressing. The other treatments were split-applied as described in the "Methods" section. Within each column, means ± SD followed by the same letter do not differ from each other based on Tukey's HSD test at a 5% probability level. CV indicates coefficient of variance.

These results highlight that, although SOM and TOC alone do not guarantee increased enzymatic activity across all functions, treatments with higher organic input — especially T3 and T6, tended to stimulate enzyme systems related to C, N, P, and S cycles. This is in line with findings by Bouhia *et al*. (2022) and Pulrolnik (2009), who report that increased organic matter contributes to microbial activity by enhancing substrate availability and improving soil microhabitat conditions. Thus, organomineral and mixed fertilization strategies may promote soil biological quality beyond their immediate nutrient supply effects.

### 3.1.5 Soil microbiology

Fungal and bacterial communities in the soil were quantified, alongside microbial biomass carbon (MBC), basal soil respiration (BSR), and the metabolic quotient (qCO2), which can be seen in Table 6.

No statistically significant differences in MBC were observed among treatments, despite numerical variation. All fertilizer sources mineral, organomineral, and organic supported comparable microbial biomass levels in the soil. This suggests that the microbial community was able to maintain similar biomass regardless of fertilizer type, potentially due to the cumulative effects of organic inputs and crop residues over time.

**Table 6**. Microbiological parameters in the soil treated with fertilizers of different sources

| Fertilizer type | MBC (mg C $g^{-1}$ $h^{-1}$) | BSR ($\mu$g $CO_2$/ g dry soil/day) | $qCo_2$ ($\mu$g $CO_2$/ g dry soil/day) | Bacterial biomass (m $g^{-1}$ dry soil) | Fungal biomass (m $g^{-1}$ dry soil) |
|---|---|---|---|---|---|
| Mineral (synthetic) | $51,9^{a}\pm4,4$ | $0,56^{c}\pm0,01$ | $0,34^{ab}\pm0,04$ | $12,05^{a}\pm 0,8$ | $17,9^{ab}\pm3,6$ |
| Organomineral-NK | $58,8^{a}\pm8,6$ | $0,69^{a}\pm0,03$ | $0,40^{a}\pm0,02$ | $9,5^{ab}\pm1,8$ | $18,5^{ab}\pm0,3$ |
| Organomineral-K | $54,4^{a}\pm4,2$ | $0,60^{ab}\pm0,01$ | $0,34^{ab}\pm0,01$ | $7,3^{b}\pm0,2$ | $23,4^{a}\pm3,0$ |
| Organic-supplied-PK | $64,6^{a}\pm15,4$ | $0,60^{ab}\pm0,02$ | $0,31^{ab}\pm0,08$ | $7,2^{b}\pm1,3$ | $17,3^{b}\pm0,7$ |
| Organic-supplied-P | $69,3^{a}\pm6,9$ | $0,58^{ab}\pm0,02$ | $0,29^{b}\pm0,0$ | $7,1^{b}\pm0,4$ | $21,6^{ab}\pm2,0$ |
| Mixed products | $63,3^{a}\pm10,1$ | $0,61^{b}\pm0,02$ | $0,38^{ab}\pm0,04$ | $9,5^{ab}\pm0,0$ | $22,4^{ab}\pm1,2$ |
| CV (%) | 17,4 | 3,5 | 14,1 | 12,9 | 12,2 |

The mixed fertilizer consisted of the K-supplied organominerals applied at planting and the digestate applied as topdressing. The other treatments were split-applied as described in the "Methods" section. Within each column, means ± SD followed by the same letter do not differ from each other based on Tukey's HSD test at a 5% probability level. CV indicates coefficient of variance.

The Organomineral-NK treatment showed the highest basal respiration rate (0.69 µg $CO_2$ $g^{-1}$ $day^{-1}$), but this value was not statistically different from most other treatments, except for the mineral fertilizer (0.56), which was significantly lower. This suggests that organic and organomineral fertilizers increase microbial respiratory activity compared to mineral inputs.

The lowest $qCO_2$ was recorded under the P-supplied organic fertilizer (0.29 µg $CO_2$ µ$g^{-1}$ C-BM $h^{-1}$), indicating greater microbial efficiency in carbon use. This value was significantly lower than that observed with Organomineral-NK (0.40). Lower $qCO_2$ values are generally desirable, as they reflect a more efficient and less stressed microbial community.

The highest bacterial biomass was observed in the soil treated with mineral fertilizer (12.05 mg $g^{-1}$ dry soil), which was statistically higher than that obtained with Organic-supplied-PK (7.2), Organic-supplied-P (7.1), and Organomineral-K (7.3). However, it did not differ significantly from Organomineral-NK and Mixed products (both 9.5 mg $g^{-1}$), indicating that some organomineral formulations may support comparable bacterial biomass. Although lower values were found in certain treatments, this does not necessarily imply reduced soil quality, as microbial balance and functional diversity such as the fungal-to-bacterial ratio also play key roles in soil health and resilience.

Fungal biomass was highest under the Organomineral-K treatment (23.4 mg $g^{-1}$ dry soil), which was statistically higher than the Organic-supplied-PK treatment (17.3 mg $g^{-1}$). However, it did not differ from the other treatments, including Mixed products (22.4), Organic-supplied-P (21.6), and mineral fertilizer (17.9). These results suggest that while some organomineral formulations may enhance fungal abundance, most treatments supported similar fungal biomass overall. Given the role of fungi in organic matter stabilization and soil aggregation, the presence of comparable fungal biomass across treatments reinforces the potential of both organomineral and organic inputs to contribute positively to soil health.

Organomineral fertilizers improve soil health but might require several years to fully manifest their benefits. The data provided evidence that reducing reliance on imported synthetic fertilizers and enhancing nutrient use efficiency in maize cultivation can be achieved using locally available waste-derived digestates or organominerals. Such practices could potentially lower fertilization costs, thereby reducing overall agricultural production expenses. It's important to note that the data presented here were derived from a greenhouse experiment. Given the variability of ecosystem services in organic farming, which are influenced by environmental changes, field studies are essential before definitive conclusions can be drawn.

## 4 CONCLUSION

In this study, five fertilizers formulated either from digestate derived from swine wastewater and layer manure (organic/biofertilizer) or from organominerals sourced from basalt rock dust and calcitic limestone demonstrated agronomic efficiency comparable to mineral fertilizers. When the mode of action was considered, organic fertilizers showed potential benefits in the short term, observable after just one growing season.

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