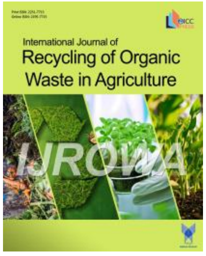

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Research Article

Coffee Innovation and Sustainability–Organomineral Fertilizers Noteworthy Results

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Abstract

Purpose: Coffee is a highly valued commodity and demands high nutritional inputs for its vegetative and reproductive development. Different sources of fertilizers are used to supply the nutritional needs of the plant. The objective of the present study was to evaluate the response of different sources and doses of special fertilizers compared to conventional mineral fertilizers in coffee plants in two consecutive crop seasons.

Method: A 4×4 factorial scheme was implemented with four fertilizers [conventional mineral, mineral with polymer, organomineral with cellulosic residue (OM-CR), organomineral with sugarcane filter cake (OM-FC)] and four doses (50, 75, 100, and 125% of the recommended dose). Coffee plant growth was evaluated: plant height, canopy diameter, growth of plagiotropic branches, and chlorophyll content. Nutrient contents in the soil and leaves, as well as coffee bean productivity, were also analyzed.

Results: In biometric data, mineral and organomineral fertilizers showed responses that were equivalent to or superior to those of the control, even when using reduced OMF doses.
For leaf N, P, and K content and soil P and K contents, the organomineral fertilizers performed better than conventional mineral fertilizers, especially in the second crop season.
There were no significant differences among the fertilizers and doses for coffee bean productivity.

Conclusion: The organomineral fertilizers, regardless of the dose, showed comparable or improved resultscompared to the conventional mineral fertilizer for the plant growth variables, potentially replacing traditional mineral fertilizers in the nutritional management of coffee crops. These results are the first report on coffee production using special fertilizers on two consecutive harvests.

Keywords: Organomineral fertilizer; Cellulosic source; Sugarcane filter cake; Coffea arabica; Coffee bean production

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1. Introduction

Coffee (*Coffea arabica* L.) is a major Brazilian crop and is commercialized worldwide (Lopes et al., 2022). However, coffee requires high technology and proper management to achieve high productivity (Aguiar and Leme, 2020). High coffee productivity involves attendance at the leading nutritional requirements of the crop. The attendance of coffee nutritional requirements is through soil fertility management, which is intended to provide all nutrients using sources of fertilizers (Guarçoni et al., 2019). Primary fertilizer sources include conventional mineral fertilizers (MF), protected MF with polymers, and organomineral fertilizers (OMF). An OMF is an association between high-nutrient inorganic fertilizers and an organic matrix (Kominko et al., 2019). A recent and significant increase in the use of OMFs was driven by a world fertilizer crisis that exposed the dependence on imports from conventional sources (Jokura, 2022; Hebebrand and Glauber, 2024). With the increasing use of OMF, there is a growing search for alternative organic raw materials to increase the efficiency of regular fertilizers (Sitzmann et al., 2025; Uddin et al., 2025). According to Costa et al. (2018), OMFs improve plant nutrient usage due to the presence of organic matter in their composition. This fact is relevant to the coffee plant, which requires high amounts of nutrients and has a low relative efficiency in using nutrients from conventional MFs. Among the main factors responsible for the low efficiency of traditional fertilizer sources, are the loss of nitrogen (N) through volatilization, phosphorus (P) by soil fixation, and potassium (K) by leaching (Caixeta et al., 2021; Araujo et al., 2020; Ribeiro et al., 2022). Thus, the greater use of nutrients when implementing OMFs and potentially lower production costs contribute to more sustainable agriculture (Garcia and Mendes, 2022). However, since OMF (organomineral fertilizer) technology is still under development, more specific studies with consistent results are needed to establish clear recommendations for its use in coffee crops. Therefore, this study aimed to evaluate the response of coffee plants to different sources and doses of special fertilizers—defined as those employing advanced technologies (e.g., organomineral formulations, polymer-coated products, or other innovative solutions) rather than conventional mineral salt-based fertilizers—compared to traditional mineral fertilizers (MF) in a commercial coffee plantation.

2. Materials and methods

2.1. Cropping area characterization

The experiment was conducted between September 2020 and July 2022 in the municipality of Indianópolis, the state of Minas Gerais , Brazil, at the coordinates 18º56’08” S, 47º56’11” W. The experimental area was located under field conditions in a commercial coffee crop area at São Sebastião farm for two consecutive harvests, the 2020/21 crop season (coffee plants in the second harvest) and the 2021/22 crop season (coffee plants in the third harvest). The area has an average altitude of 911 m.a.s.l. and an Aw climate (rainy summer with dry winter) (Antunes, 1986). The soil of the experimental area was classified as dystrophic Red Latosol (Oxisol), with a clayey texture, according to the Brazilian Soil Classification System (Embrapa, 2018). This corresponds to the Oxisol order in the Soil Taxonomy (Soil Survey Staff, 2014). Further, soil details are provided in “Soil and leaf characterization” section.

2.2. Experimental design

A randomized block design was used in a 4×4 factorial scheme with four replications, generating 64 experimental plots with six coffee plants each. The total experimental area was 1,020 m². Four fertilizers were tested: conventional mineral, mineral with polymer (Kimberlit Agrociências), organomineral with cellulose residue, and organomineral with sugarcane filter cake. Each was applied at four doses (50, 75, 100, and 125%) based on the recommendation for coffee cultivation for the first crop year (350 kg/ha N; 50 kg/ha P_2O_5; 300 kg/ha K_2O) and the second crop year (500 kg/ha N; 100 kg/ha P_2O_5; 80 kg/ha K_2O) (Table 1).

2.3. Fertilizers characterization

The fertilizers had specific formulations (Table 2) to supply N, P, and K. The conventional mineral fertilizer was formulated as 45-00-00, 12-52-00, and 00-00-60(percentages of N-P_2O_5-K_2O, respectively). The formulations 45-00-00, 12-52-00, and 01-00-57 were used in the mineral fertilizer with polymer. The formulations for the OMF based on cellulose residues were 25-00-00, 05-26-00, and 00-00-32.The formulations 29-00-00, 06-30-00, and 00-00-35 were used in the OMF containing sugarcane filter cake as the organic matrix. The raw fertilizers used for the OMFs were identical to the conventional mineral fertilizers: urea as the N source, monoammonium phosphate as the N and P source, and KCl as the K source. The chemical characterization of the OMF was carried out at the Lab Fert Laboratory in Araguari, Brazil. The chemical attributes of the sugarcane filter cake were analyzed at the Exata Laboratory in Jataí, Brazil.

2.4. Cropping area historic

The coffee crop (Mundo Novo variety) was established in December 2017 using conventional soil preparation with harrowing (3.8×0.7 m). Liming (2 ton/ha) was performed to correct the soil for subsequent fertilization.

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Table 1. Fertilizer sources, nutrient amount according to efficiency rate, and fertilizer recommendation for coffee cultivation

Year 1 (crop season 2020/21)				Year 2 (crop season 2021/22)			
Fertilizer Source Conventional mineral	N, P_2O_5, K_2O* (kg/ha)	Dose %	Final Amount (kg/ha)	Fertilizer Source Conventional mineral	N. P_2O_5. K_2O* (kg/ha)	Dose %	Final Amount (kg/ha)
45-00-00	175	50	388.8	45-00-00	250	50	555.6
45-00-00	263	75	584.4	45-00-00	375	75	833.3
45-00-00	350	100	777.7	45-00-00	500	100	1111.1
45-00-00	438	125	973.3	45-00-00	625	125	1388.9
12-52-00	25	50	48.1	12-52-00	50	50	96.2
12-52-00	38	75	73.1	12-52-00	75	75	144.2
12-52-00	50	100	96.2	12-52-00	100	100	192.3
12-52-00	63	125	121.2	12-52-00	125	125	240.4
00-00-60	150	50	250.0	00-00-60	40	50	66.7
00-00-60	225	75	375.0	00-00-60	60	75	100.0
00-00-60	300	100	500.0	00-00-60	80	100	133.3
00-00-60	375	125	625.0	00-00-60	103	125	171.7
Mineral with polymer	kg/ha	%	kg/ha	Mineral with polymer	kg/ha	%	kg/ha
45-00-00	175	50	388.8	45-00-00	250	50	555.6
45-00-00	263	75	584.4	45-00-00	375	75	833.3
45-00-00	350	100	777.7	45-00-00	500	100	1111.1
45-00-00	438	125	973.3	45-00-00	625	125	1388.9
12-52-00	25	50	48.1	12-52-00	50	50	96.2
12-52-00	38	75	73.1	12-52-00	75	75	144.2
12-52-00	50	100	96.2	12-52-00	100	100	192.3
12-52-00	63	125	121.2	12-52-00	125	125	240.4
01-00-57	150	50	85.5	01-00-57	40	50	70.2
01-00-57	225	75	394.7	01-00-57	60	75	105.3
01-00-57	300	100	526.3	01-00-57	80	100	140.4
01-00-57	375	125	657.9	01-00-57	103	125	180.7
Organominer l with cellulose	kg/ha	%	kg/ha	Organominer l with cellulose	kg/ha	%	kg/ha
25-00-00	175	50	700.1	25-00-00	250	50	1000.0
25-00-00	263	75	1052.1	25-00-00	375	75	1500.0
25-00-00	350	100	1400.0	25-00-00	500	100	2000.0
25-00-00	438	125	1752.0	25-00-00	625	125	2500.0
05-26-00	25	50	96.2	05-26-00	50	50	192.3
05-26-00	38	75	146.2	05-26-00	75	75	288.5
05-26-00	50	100	192.3	05-26-00	100	100	384.6
05-26-00	63	125	242.3	05-26-00	125	125	480.8
00-00-32	150	50	468.8	00-00-32	40	50	125.0
00-00-32	225	75	703.1	00-00-32	60	75	187.5
00-00-32	300	100	937.5	00-00-32	80	100	250.0
00-00-32	375	125	1171.8	00-00-32	103	125	321.9
Organominer l with filter cake	kg/ha	%	kg/ha	Organominerl with filter cake	kg/ha	%	kg/ha
29-00-00	175	50	603.4	29-00-00	250	50	862.1
29-00-00	263	75	906.9	29-00-00	375	75	1293.1
29-00-00	350	100	1206.9	29-00-00	500	100	1724.1
29-00-00	438	125	1510.3	29-00-00	625	125	2155.2
06-30-00	25	50	83.3	06-30-00	50	50	166.7
06-30-00	38	75	126.6	06-30-00	75	75	250.0
06-30-00	50	100	166.6	06-30-00	100	100	333.3
06-30-00	63	125	210.0	06-30-00	125	125	416.7
00-00-35	150	50	428.6	00-00-35	40	50	114.3
00-00-35	225	75	642.9	00-00-35	60	75	171.4
00-00-35	300	100	857.1	00-00-35	80	100	228.6
00-00-35	375	125	1071.4	00-00-35	103	125	294.3

* The additional N score in the phosphate formulations was deducted from the N formulations.

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Table 2. Chemical characterization of fertilizers and the organic matrix of organomineral fertilizers

Fertilizer	Characteristics				
Conventional mineral	Format	N	P	K	C/N ratio
45-00-00	grany	45	0	0	---
12-52-00	bran	12	52	0	---
00-00-60	grany	0	0	60	---
Mineral with polymer	Format	N	P	K	C/N ratio
45-00-00	grany	45	0	0	---
12-52-00	grany	12	52	0	---
01-00-57	grany	1	0	57	---
Organomineral with cellulose*	Format	N	P	K	C/N ratio
25-00-00	bran	25	0	0	1/1
05-26-00	grany	5	26	0	1/1
00-00-32	grany	0	0	32	1/1
Organomineral with filter cake*	Format	N	P	K	C/N ratio
29-00-00	bran	29	0	0	1/1
06-30-00	bran	6	30	0	1/1
00-00-35	bran	0	0	35	1/1
Organic matrix	TOC	Total N		Total P_2O_5	Soluble K_2O
Celulose	17.7	1.0		0.70	0.4
Filter cake	29.6	2.7		3.34	< D.L.

* Values considering the fertilizer raw state. N: sulfuric digestion method; P and K: perchloric nitro digestion method read atomic absorption. TOC: total organic carbon. D.L.: Detection level

At coffee planting (3,759 plants/ha, 1.43 plants/m, spaced by 3.8 m between planting lines), chicken manure (5,000 kg/ha) and phosphate fertilizer (500 kg/ha Top Phos® equivalent to 140 kg/ha of P_2O_5) were incorporated. The fertilizer contained 3% N, 28% P, 10% Ca, 5% S, 0.12% Cu, 0.12% B, 0.3% Mn, and 0.3% Zn. During the coffee crop formation (October and March of 2018 and 2019), the fertilizati on was carried out using a nitrogen source (nitric and ammonia nitrogen from the formulation 27-00-00, 740 kg/ha applied in seven parcels of 105.7 kg/ha) and phosphorus source (00-18-00, 277.7 kg/ha). In addition, foliar fertilization complemented the micronutrients. Mechanical weeding and glyphosate were carried out to control invasive plants according to the manufacturer's instructions for each species of infesting plants. Additionally, unproductive branches were removed from each plant. The irrigation consisted of an automated dripping system (15 mm water blade per week during dry seasons).

2.5. Soil and leaf characterization

According to Embrapa (2017), the soil texture was determined in layers of 0-0.2 and 0.2-0.4 m (Table 3). Textural analysis was conducted at the Soil Management Laboratory (LAMAS) at the Federal University of Uberlândia. Soil and leaf chemical analyses were performed at the Safrar Agricultural Analysis Laboratory in Uberlândia, Brazil.

Table 3. Soil texture and chemical characterization (0-0.2 and 0.2-0.4 m) and coffee leaf characterization at the beginning of the experiment

Soil physical characterization			
Depth (m)	Sand	Silt	Clay
	---------- g/kg ----------		
0-0.2	321	191	488
0.2-0.4	412	220	368

Soil chemical characterization									
Depth (m)	pH	K	Ca	Mg	Al	H+Al	BS	t	T
	water	---------- cmolc/dm^3 ----------							
0-0.2	5.9	0.2	2.5	0.6	0	3.8	3.32	3.32	7.12
0.2-0.4	5.7	0.2	1.8	0.4	0	3.8	2.43	2.43	6.23
Depth (m)	P meh-1	V	m	SOM	B	Cu	Fe	Mn	Zn
	Mg/dm^3	---- % ----		dag/kg	---------- mg/dm^3 ----------				
0-0.2	8.9	47	0	3.0	0.55	5.10	47	7.8	3.6
0.2-0.4	7.4	39	0	2.9	0.56	4.50	43	3.8	2.2

Leaf chemical characterization										
N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
---------- g/kg ----------						---------- mg/kg ----------				
34	1.9	23	12.4	3.3	1.8	38	7	220	103	9

Sand, silt, and clay by the pipette method (slow stirring). P, K: HCL 0.05 mol/L + H_2SO_4 0.0125 mol/L. P available: Mehlich extractor-1. Ca, Mg, Al: KCl 1 mol/L. H+Al: SMP buffer solution at pH 7.5. SB: sum of bases. t = effective CTC. T = CTC at pH 7. V: base saturation. m: aluminum saturation (Embrapa, 2017). SOM (soil organic matter): colorimetric method. B: $BaCl_2.2H_2O$ 0.0125% hot. Cu, Fe, Mn, Zn: DTPA 0.005 mol/L + TEA 0.1 mol/L + $CaCl_2$ 0.01 mol/L at pH 7.3. Leaf N: Sulfuric digestion. Leaf P, K, Ca, Mg, S, Cu, Fe, Mn, Zn: perchloric nitro digestion. B: incineration.

2.6. Crop management

The necessary cultural practices, such as weed, pest, and disease control, were carried out through the coffee crop cycle. The only difference among treatments was in fertilization management. Before the fertilizer's application, the soil samples for fertilizer recommendation were collected in September 2020 and 2021 for physical and chemical characterization. Fertilizer doses were calculated based on the crop's expected productivity and class of nutrient availability in the soil. The conventional mineral fertilizers were applied in three lots (October, December, and January); the mineral fertilizers with polymer and OMFs with cellulose or sugarcane filter cake were applied in two lots (Octoberand December).

2.7. Evaluations: plant growth and chlorophyll

The increment rate of plagiotropic branches was measured with a graduated ruler from the branch's insertion point to the terminal bud (cm). Canopy (shoot) diameter: measured with a graduated ruler, taking the two branches toward the planting lines and with the most extended length (cm). Plant height: measured with a ruler from ground level to the insertion point of the terminal bud (cm). Chlorophyll: measured using a portable device (SPAD-502 Plus

Minolta) in coffee leaves from 8:00 to 11:00h in the morning.

2.8. Evaluations: nutrient contents in soil and leaves

Coffee leaf sampling occurred in January 2021 and 2022 to determine the coffee leaf contents of N, P, and K (g/kg). Forty to 50 pairs of leaves were collected from the 3^{rd} and 4^{th} pairs of productive branches in the four quadrants of the middle third of the four central coffee plants in each parcel. Soil samples were collected in May 2021 and 2022 with an auger probe at 0-0.2 m depth in the representative parcel (area of the 4 inner coffee plants in each experimental parcel) to determine the P and K content in the soil. The collected soil and leaves were placed in plastic, and then perforated paper bags were duly identified. Safrar Agricultural Analysis Laboratory analyzed the samples to determine macronutrient contents according to Bataglia et al. (1983).

2.9. Evaluations: coffee bean productivity

The harvest was carried out in each representative parcel by manually stripping the cloth. The beginning of harvest was determined as a function of the lowest possible percentage of unripe fruits on the plant (< 10%). After determining the volume produced by the plot, a 10 L sample was taken, which was dried in a yard. After reaching 11% moisture, the mass and volume of bean coffee were determined. Subsequently, the samples were processed, and the coffee's mass, volume, and moisture were again determined. Based on the relation between the volume of the 10 L sample of coffee harvested in the cloth and the mass of the processed sample, the production per plot was determined and expressed in 60 kg bags/ha.

2.10. Statistical analyses

The extreme values (outliers) were analyzed in the data of each variable studied using boxplot graphs of the data residuals generated in the SPSS Statistics® software (Chambers et al., 1983). Identified outliers were treated as missing data and replaced by values estimated by the least sum of squares residuals method. Then, each replaced outlier had a degree of freedom removed from the experimental error in the subsequent analysis of variance (ANOVA-F-test) (Pimentel Gomes and Garcia 2002).

SPSS Statistics® software was also used to confirm the normality of the residual distribution (basic assumptions for ANOVA, $p > 0.01$) by Shapiro-Wilk and the Pearson correlation coefficients between the variables. Fundamentally, the data should be normally distributed and without outliers to avoid errors associated with the computation and interpretation of the Pearson correlation (Figueiredo Filho and Silva Jr., 2009). After confirming the assumptions, the ANOVA (F test) was performed using the Sisvar® statistical program. When significant differences were observed between the treatments (fertilizer doses), the regressions were studied if the "a" coefficient was significant ($p_a \leq 0.05$) and the coefficient of determination (R^2) was equal to or greater than 70%. Graphs were generated by Sigma Plot® software.

3. Results and discussion

The results of the chlorophyll content and the biometric variables (plant height, stem diameter, and development of the plagiotropic branches) in both evaluated crop seasons (2020/21 and 2021/22) are presented in Table 4. In the 2020/21 crop season, the chlorophyll content presented an interaction between factors ($p \leq 0.05$), and plant height was affected by the fertilizer source factor ($p \leq 0.05$). As for the second crop season (2021/22), the plant canopy diameter presented an interaction between factors ($p \leq 0.05$), and the plagiotropic branch was affected by the fertilizer source factor ($p \leq 0.05$). The tested fertilizers and doses did not interfere with the development of the coffee plagiotropic branches. The leaf chlorophyll content presented no significant difference between the mineral sources (mineral and organomineral) in the first crop season (2020/21).

The doses studied within each fertilizer source interfere with the chlorophyll content of coffee plants in the first crop season (2020/21). The OM-CR at 125% of the recommended dose for coffee crops showed promising effects on leaf chlorophyll in the first crop season and coffee canopy diameter in the second crop season; however, only the Mineral-P source presented a quadratic polynomial model that fitted the data [significant ($p \leq 0.05$) "a" coefficient $R^2 \geq 70\%$] (Fig. 1). According to such a model, the highest leaf chlorophyll was observed when 86.70% of the recommended dose of Mineral-P. The studied doses did not interfere with the coffee plant's height. Still, the Mineral-P fertilizer showed remarkable gains in plant height (about 248 cm), with no differences compared to other OMFs (about 245 cm) and superior to the MF (about 242 cm) (Table 4). The canopy diameter was influenced by the fertilizer sources and doses tested only in the second crop season (2021/22); however, only the MF and the OM-CR source presented a regression model that significantly adjusted to the data [significant ($p \leq 0.05$) "a" coefficient $R^2 \geq 70\%$] (Fig. 2). Despite the accused significant models, the average coffee canopy diameter among the treatments varied from 182.94 to 184.38 cm, and there was no clear tendency of canopy diameter growth in coffee plants with rising fertilizer doses.

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Table 4. Statistics and averages of chlorophyll, plant height (cm), canopy diameter (cm), and plagiotropic branch (cm) for fertilizers and doses in coffee in two consecutive crop seasons

Dose	2020/21 crop season				2021/22 crop season			
	Mineral	Mineral-P	OM-CR	OM-FC	Mineral	Mineral-P	OM-CR	OM-FC
	Chlorophyll							
50	84.29 a	86.46 a	94.45 a	84.61 a	72.31	69.40	69.79	70.21
75	90.29 a	102.19 a	93.44 a	77.51 a	70.81	70.32	70.58	68.91
100	73.90 a	103.05 a	77.50 a	93.62 a	69.02	68.35	71.41	72.27
125	84.98 ab	84.27 ab	112.18 a	70.73 b	67.05	70.71	68.10	72.58
Average	83.36	93.99	94.39	81.62	69.80	69.70	69.97	70.99
$P_{fertilizer}$	0.04				0.50			
P_{dose}	0.90				0.84			
$P_{interaction}$	0.03*				0.06			
C.V. (%)	18.03				3.79			
	Plant height							
50	240.06	246.58	243.31	247.44	278.50	277.75	276.75	281.00
75	248.06	249.12	249.31	245.81	281.5	275.25	282.00	280.25
100	238.63	247.87	242.62	242.31	277.00	277.75	276.25	276.75
125	241.81	246.58	246.68	243.37	280.75	279.00	277.75	273.5
Average	242.14 B	248.09 A	245.23 AB	244.73 AB	279.44	277.44	278.19	277.88
$P_{fertilizer}$	0.03*				0.84			
P_{dose}	0.06				0.65			
$P_{interaction}$	0.77				0.76			
C.V. (%)	2.23				2.33			
	Canopy diameter							
50	198.50	204.75	198.31	198.41	186.50 a	187.25 a	175.50 a	184.25 a
75	202.69	193.38	201.38	200.69	177.75 a	190.00 a	184.50 a	187.25 a
100	194.31	197.38	205.13	201.56	182.00 a	179.75 a	193.00 a	182.50 a
125	199.94	192.33	197.38	201.00	185.50 a	180.50 a	183.25 a	182.75 a
Average	198.86	196.96	200.55	200.42	182.94	184.38	184.06	184.19
$P_{fertilizer}$	0.61				0.94			
P_{dose}	0.87				0.88			
$P_{interaction}$	0.48				0.02*			
C.V. (%)	4.33				4.31			
	Plagiotropic branch							
50	20.51	15.29	16.80	17.15	95.24	97.02	90.60	98.21
75	11.25	15.90	15.59	17.12	98.39	96.14	98.60	101.39
100	16.50	17.06	15.45	18.74	100.74	96.02	98.62	99.85
125	18.60	18.08	14.37	16.15	98.81	96.19	94.01	98.30
Average	16.72	16.58	15.55	17.29	98.29 A	96.34 A	95.46 A	99.43 A
$P_{fertilizer}$	0.57				0.05*			
P_{dose}	0.23				0.07			
$P_{interaction}$	0.15				0.58			
C.V. (%)	21.44				4.42			

Mineral: Conventional mineral fertilizer. Mineral-P: mineral fertilizer with polymer. OM-CR: organomineral with cellulosic residue. OM-FC: organomineral with sugarcane filter cake. Similar letters, lowercase in column and uppercase in line, do not differ by Tukey's test of averages ($p \leq 0.05$).

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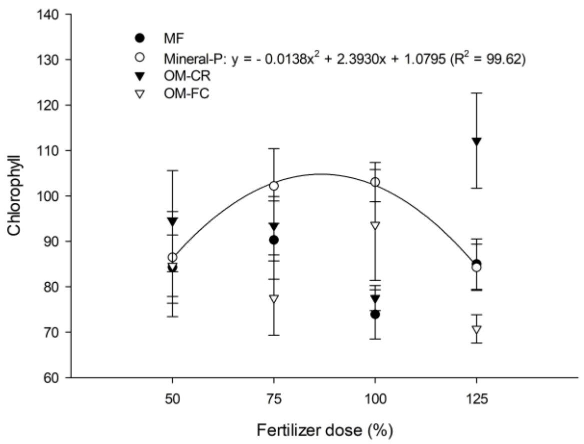

Figure 1. Coffee leaf chlorophyll in the 2020/21 crop season.
MF: conventional mineral fertilizer. Mineral-P: mineral fertilizer with polymer. OM-CR: organomineral with cellulosic residue. OM-FC: organomineral with sugarcane filter cake. Bars on each average represent the standard error

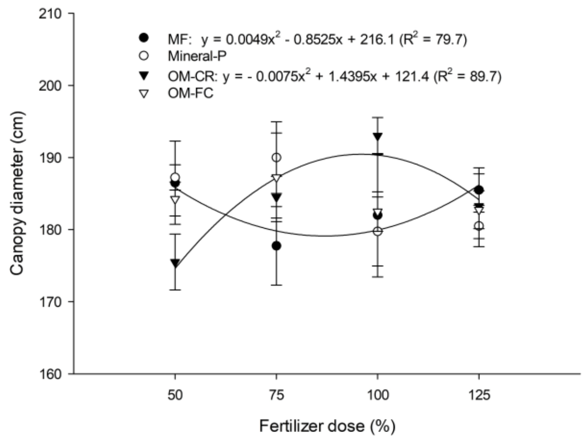

Figure 2. Coffee canopy diameter in the 2021/22 crop season.
MF: conventional mineral fertilizer. Mineral-P: mineral fertilizer with polymer. OM-CR: organomineral with cellulosic residue. OM-FC: organomineral with sugarcane filter cake. Bars on each average represent the standard error

The effect of fertilizer sources and doses on the development of the coffee plagiotropic branch presented no significant differences among the levels in each factor (Table 4). Table 5 presents the N, P, and K foliar contents with fertilizer sources and applied doses in both evaluated crop seasons (2020/21 and 2021/22). In the first crop season (2020/21), the dose factor influenced the foliar N content, but the data did not fit any significant regression model, presenting very low coefficients of determination (R^2). In the second crop season (2021/22), the interaction "fertilizer source × dose" was significant for foliar N contents (Table 5). Regression models for foliar N contents are presented in Fig. 3. As it is shown, only Mineral-P and OM-CR presented data that fitted a linear model for the variable in question; the other fertilizer sources presented quadratic regression models. Except for the MF treatment, the tendencies indicate a coffee leaf N content rise as the fertilizer dose increases. The OMFs studied stood out in the N content in coffee leaves compared to conventional mineral fertilizers. According to Magela et al. (2019), OMFs provide similar or superior results in developing maize (*Zea mays* L.). The OMFs could provide nutrients in high amounts over time, replacing MFs and maintaining and improving soil fertility. These effects result from the organic matter present in OMFs, which facilitates their absorption and assists in transporting photoassimilates produced by the plants (Almeida et al., 2019). As a complementary analysis, a nutritional analysis of the leaf's nutrient content is also necessary in response to soil fertilization. Conventional MF and OM-CR were adjusted to regression models For the foliar P content in the 2020/21 crop season (Fig. 4). The data obtained using the Mineral-P and the OM-FC did not fit the regression models. According to the MF and OM-CR, the maximum coffee leaf P contents were observed at 89.50 and 84.29% of the recommended dose, respectively.

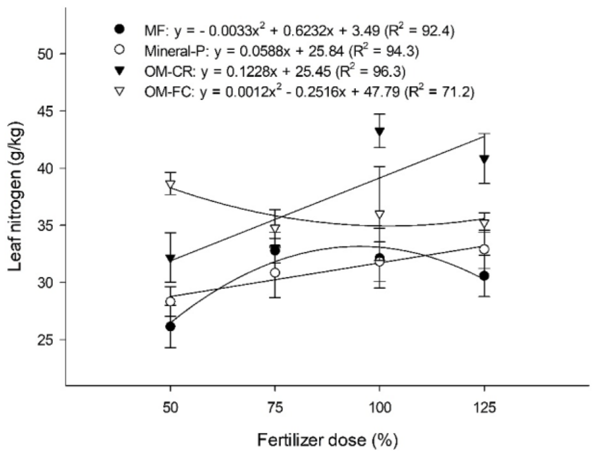

Figure 3. Nitrogen content in coffee leaves from the 2021/22 crop season. MF: conventional mineral fertilizer. Mineral-P: mineral fertilizer with polymer. OM-CR: organomineral with cellulosic residue. OM-FC: organomineral with sugarcane filter cake. Bars on each average represent the standard error

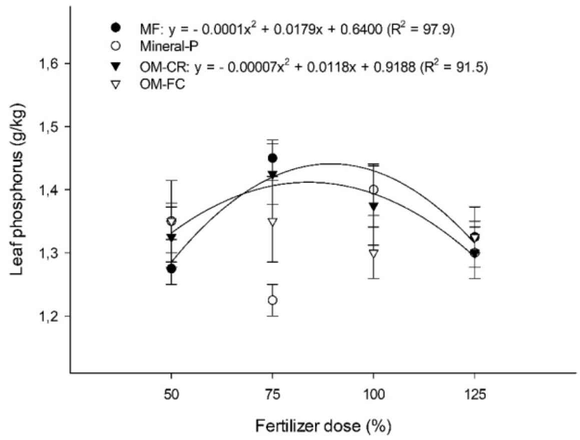

Figure 4. Phosphorus content in coffee leaves from the 2020/21 crop season. MF: conventional mineral fertilizer. Mineral-P: mineral fertilizer with polymer. OM-CR: organomineral with cellulosic residue. OM-FC: organomineral with sugarcane filter cake. Bars on each average represent the standard error

Table 5. Statistics and averages of nitrogen (N), phosphorus (P), and potassium (K) contents in coffee leaf cropped with fertilizers in two consecutive crop seasons

Dose	2020/21 crop season				2021/22 crop season			
	Mineral	Mineral-P	OM-CR	OM-FC	Mineral	Mineral-P	OM-CR	OM-FC
	N							
50	29.05	30.63	28.25	30.30	26.15b	28.32b	32.17b	38.65a
75	27.80	27.30	29.08	26.83	32.77a	30.85a	33.55a	34.77a
100	29.20	29.10	28.78	29.17	32.12b	31.82b	38.22a	36.02b
125	28.45	30.32	29.67	29.07	30.57b	32.90b	40.85a	35.22ab
Average	28.63	29.13	28.94	28.85	30.41	30.97	36.2	36.17
$P_{fertilizer}$	0.74				0.00*			
P_{dose}	0.002*				0.002*			
$P_{interaction}$	0.08				0.002*			
C.V. (%)	4.47				13.17			
	P							
50	1.28a	1.35a	1.32a	1.35a	1.47	1.75	1.75	1.73
75	1.45a	1.22b	1.42a	1.35ab	1.50	1.80	1.90	1.78
100	1.40a	1.40a	1.37a	1.30a	1.28	1.55	1.65	1.83
125	1.33a	1.30a	1.30a	1.33a	1.45	1.73	1.86	1.76
Average	1.36	1.32	1.36	1.33	1.42B	1.71A	1.79A	1.81 A
$P_{fertilizer}$	0.42				0.00*			
P_{dose}	0.18				0.01*			
$P_{interaction}$	0.03*				0.43			
C.V. (%)	6.28				8.66			
	K							
50	24.50	24.25	25.50	25.25	25.00	28.25	27.25	29.00
75	26.75	23.50	27.50	25.50	22.75	29.00	30.25	30.25
100	26.50	25.00	27.50	23.75	22.50	27.50	27.75	30.50
125	24.00	24.50	24.50	25.75	24.25	29.75	28.00	29.50
Average	25.44AB	24.31B	26.25A	25.06AB	23.62B	28.63A	28.31A	29.81A
$P_{fertilizer}$	0.04*				0.00*			
P_{dose}	0.25				0.49			
$P_{interaction}$	0.18				0.29			
C.V. (%)	7.58				7.30			

Mineral: Conventional mineral fertilizer. Mineral-P: mineral fertilizer with polymer. OM-CR: organomineral with cellulosic residue. OM-FC: organomineral with sugarcane filter cake. Similar letters, lowercase in column and uppercase in line, do not differ by Tukey's test of averages ($p \leq 0.05$).

The leaf P content in the 2021/22 crop season showed a significant isolated effect only for the fertilizer source and dose factors (Table 5); however, none of the models fit a linear or quadratic model of the coffee leaf P content in the 2021/22 crop season. Leaf nutrient contents serve as indicators of soil nutrient availability and plant nutritional status (Mao et al., 2020). Mao et al. (2020) found that in the initial year of using OMFs, there were no discernible distinctions compared to MF. They also noted that the effects of OMFs become more prominent over time due to the elevated leaf P content observed in OMFs versus MFs in the subsequent year. These outcomes stem from the gradual and sustained nutrient release provided by OMFs, leading to prolonged residual effects and soil enhancements (Ojo et al., 2014; Crusciol et al., 2020). Apart from enduring impacts, research indicates that higher doses of OMFs can enhance nutrient accessibility within a single growing season. For example, Queiroz et al. (2017) reported that increased OMF dosages resulted in higher lettuce biomass due to improved nutrient availability during the crop's growth cycle.

The doses analyzed in this study did not interfere with K content in coffee leaves, with only the fertilizer factor presenting a significant effect. Organomineral fertilizers showed similar to superior leaf K content in coffee plants in both crop seasons (Table 4). Table 6 shows the soil P and K content for both crop seasons (2020/21 and 2021/22). The evaluated fertilizers and the studied doses presented a significant interaction in the 2021/22 crop season for the soil P content. Regardless of the analyzed dose, the use of OM-CR presented better results than the other sources in the 2021/22 crop season, showing the superiority of the OM-CR when aiming to increase P in the soil.

Table 6. Statistics and averages of phosphorus (P) and potassium (K) contents in soil from coffee cropped with fertilizers in two consecutive crop seasons

Dose	2020/21 crop season				2021/22 crop season			
	Mineral	Mineral-P	OM-CR	OM-FC	Mineral	Mineral-P	OM-CR	OM-FC
	P							
50	13.90	15.10	24.93	20.40	44.15ab	26.43c	50.02a	28.78bc
75	20.35	22.17	23.03	20.33	33.63a	28.63a	40.45a	38.45a
100	16.83	24.95	14.48	18.88	25.57b	29.38b	60.97a	32.85b
125	15.22	25.05	20.57	15.42	36.43b	34.53b	71.48a	24.80b
Average	16.58	21.88	20.75	18.76	34.94	29.73	55.73	31.22
$P_{fertilizer}$	0.09				0.00			
P_{dose}	0.52				0.17			
$P_{interaction}$	0.11				0.00*			
C.V. (%)	31.58				22.08			
	K							
50	145.75	118.00	116.25	93.25	65.75	48.50	59.00	90.75
75	144.75	114.75	89.00	111.50	56.00	62.50	67.50	82.75
100	147.25	107.50	115.00	124.50	57.25	62.00	84.75	76.75
125	124.50	119.50	117.00	150.75	60.50	70.50	66.75	76.50
Average	140.56a	114.94b	109.31b	120.00ab	59.88b	60.88b	69.50ab	81.69a
$P_{fertilizer}$	0.004*				0.00*			
P_{dose}	0.44				0.89			
$P_{interaction}$	0.09				0.22			
C.V. (%)	19.79				22.92			

Mineral: conventional mineral fertilizer. Mineral-P: mineral fertilizer with polymer. OM-CR: organomineral with cellulosic residue. OM-FC: organomineral with sugarcane filter cake. Similar letters, lowercase in column and uppercase in line, do not differ by Tukey's test of averages ($p \leq 0.05$).

The dose relationships with the fertilizer sources for soil P content in the 2021/22 crop season are shown in Fig. 5. Only the mineral sources fitted regression models [significant ($p \leq 0.05$) "a" coefficient $R^2 \geq 70\%$]. The soil P content in the MF showed a significant quadratic performance, with an increasing pattern in soil P contents after doses higher than 95.34% of the recommended dose for the coffee crop. The Mineral-P fertilizer presented a significant linear performance, increasing the soil P content at about 0.1 mg/dm^3 for every 1% rise in the Mineral-P dose. Only fertilizer sources affected the soil K content in both crop seasons (2020/21 and 2021/22). Regardless of the studied doses in the 2020/21 crop season, the MF and OM-FC stood out regarding the soil K content. In the 2021/22 crop season, the OMFs presented higher soil K contents in the soil, and the OM-FC differed from the mineral sources.

Frazão et al. (2021) emphasize the importance of long-term field experiments to evaluate the residual effect of OMFs and their potential regarding nutrient losses in the soil. According to the authors, such matter is of particular interest in highly weathered tropical soils where OMF may even be considered a viable alternative to replace mineral fertilizers in the growth and production of corn and soybean plants. A perennial crop such as coffee must be evaluated for at least two crop cycles to reduce the effect of biennial and any climatic adversity in the environment. The study of a perennial crop evidenced that the use of OM-CR was a promising source of fertilizer in the second coffee crop season (2021/22) through the increment of P in the soil compared to other fertilizer sources, regardless of the evaluated dose. Although the organomineral works as a slow-release fertilizer due to the presence of its organic matrix (Sakurada et al., 2016), its use promotes an increase in the availability of P in the soil, as well as a source of conventional fertilizer (Frazão et al., 2021).

In the present study, the MF only showed a good response due to doses higher than the recommended dose for the crop in the second coffee crop season. This improved fertilization is due to the low availability of P in tropical soils due to precipitation and adsorption processes of inorganic forms, with a higher degree of fixation in clayey soils containing iron and aluminum ions (Lima, 2020). Corroborating with the studies by Jorhi et al. (2015) and Santos et al. (2016), the soils with the highest P fixation potential were proportional to the highest clay content, indicating frequent application of high P fertilizer amounts. Such doses ensure greater efficiency in using the soil nutritional content for plant development in soils with low natural P availability or high potential for fixing it (Cabral et al., 2020) .Coffee productivity in the 2020/21 and 2021/22 crop seasons is presented in Table 7. Regardless of the dose, the fertilizers tested did not interfere with the coffee bean productivity plant in any of the evaluated crop seasons.

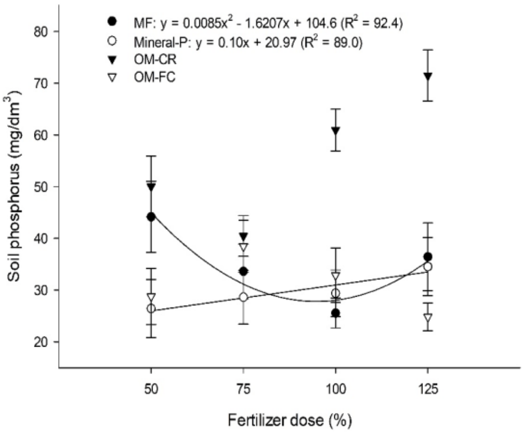

Figure 5. Phosphorus content in the soil from the 2021/22 crop season. MF: conventional mineral fertilizer. Mineral-P: mineral fertilizer with polymer. OM-CR: organomineral with cellulosic residue. OM-FC: organomineral with sugarcane filter cake. Bars on each average represent the standard error

Table 7. Statistics and averages of coffee bean productivity (60 kg bags/ha) from coffee cropped with fertilizers in two consecutive crop seasons

	2020/21 crop season				2021/22 crop season			
Dose	Mineral	Mineral-P	OM-CR	OM-FC	Mineral	Mineral-P	OM-CR	OM-FC
	Grain productivity							
50	8.40	17.57	9.22	18.32	64.54	67.06	77.70	70.06
75	12.60	18.80	16.60	35.50	69.38	74.49	68.16	78.80
100	17.05	10.65	14.60	13.70	58.97	80.55	70.90	81.14
125	14.78	8.52	19.80	16.15	72.18	72.21	71.92	66.26
Average	13.21	13.89	15.06	20.92	66.27	73.58	72.17	74.07
$P_{fertilizer}$	0.09				0.16			
P_{dose}	0.10				0.81			
$P_{interaction}$	0.12				0.22			
C.V. (%)	59.19				15.08			

Mineral: conventional mineral fertilizer. Mineral-P: mineral fertilizer with polymer. OM-CR: organomineral with cellulosic residue. OM-FC: organomineral with sugarcane filter cake. Similar letters, lowercase in column and uppercase in line, do not differ by Tukey's test of averages ($p \leq 0.05$).

The current study observed that mineral and organomineral fertilizers affected coffee responses in the first and/or the second crop season, except for yield, which was similar among the treatments studied. The results indicate that fertilization with regular MFs or OMFs in coffee crops generates comparable results, even in lower OMF doses. Other crops also responded with similar results for minerals and OMFs. Crusciol et al. (2020) studied mineral and OMFs in sugarcane (*Saccharum officinarum* L.). In addition, they reported similar growth results, but sugarcane stems and sugar production showed a linear increase as a function of fertilizer doses. Sousa et al. (2021) evaluated sugarcane plant height with doses of OMF based on sewage sludge and found no differences from mineral fertilizers. Teixeira et al. (2014) also evaluated sugarcane. They found that the OMF dose can be reduced by about 18.8% of the recommended dose, which still presents results similar to those of the regular recommended dose. Corroborating with Mota et al. (2019), who observed that OMF at doses equivalent to, or even lower than, the recommended mineral dose (100%) showed benefits to the development of the soybean (*Glycine max* L.) crop. These benefits are due to the gradual release of nutrients into the soil solution (Aguilar et al., 2019; Souza et al., 2020).

For the different sources of fertilizers, regardless of the dose, there was no interference in the productivity of the coffee beans. A similar result was found by Silva et al. (2022) in potatoes (*Solanum tuberosum* L.), where no significant differences in productivity were observed between OMF and the recommended MF dose. However, despite the use of OMFs promoting the same results as MF, not interfering with the potato development, it was observed for the yield of tubercles of "special class" and the accumulation of total dry mass that the dose of 40% of the recommended dose as OMF provided satisfactory results, being an alternative in reducing the use of MF. Fernandes et al. (2021) also pointed out that using OMFs is a feasible source for coffee crops as it guarantees the favorable properties of soil organic matter, avoiding the lack of uniformity in the nutritional sources of exclusively organic fertilizers. Araujo et al. (2020) found that using OMF in millet (*Pennisetum glaucum* (L.) R. Br.) in sandy soil led to an increase in grain production due to the residual effect with this source, mainly when used in higher doses. The evolution of these fertilizers is an essential premise in the search for alternative sources of fertilization that promote significant increment and efficiency in the use of nutrients. As well as Crusciol et al. (2020) also found that the OMF efficiently met the sugarcane crop's needs and could completely replace the conventional MF. However, its influence on the sugar yield is lower than on the stalk yield, with outstanding performance in the sugarcane plant development. Finally, Garcia and Mendes (2022) did not observe a statistical difference in growth variables, nutrition, and dry matter production of sugarcane plants as a function of sources and doses of P from OMF compared to MF.Organomineral fertilizers are an excellent source of nutrients because they are sustainable, supply the soil and the plant, and meet the environmental system's demands (Timsina, 2018). Therefore, this study's results indicate that organominerals can be a viable and promising alternative to conventional mineral fertilizers in coffee agriculture, offering a potential benefit for plant and soil improvements. Our results open new perspectives for optimizing sustainable coffee agriculture, and it is a pioneer study on the learning of organomineral mineral uses in coffee crops.

4. Conclusion

The conventional mineral (MF) and organomineral (OMF) fertilizer sources delivered equivalent results in coffee plants, even when reduced OMF rates were applied. In the second harvest evaluated, an increase in leaf N concentration was observed when OMFs were used, whereas leaf P and K concentrations were higher for both the OMF treatments and the Mineral-P source. Additionally, in that same harvest, the OM-CR product showed a greater response regardless of the application rate, in contrast to the Mineral-P source, which exhibited a linear increase in soil P content as rates increased. No differences were detected in coffee bean yield between mineral and organomineral fertilizers in either of the two harvests, indicating that organomineral fertilizers can perform similarly to conventional mineral fertilizers.

Authors Contribution

RPM: experimental guidance, data curation, writing of the original draft. RC: experimental planning, methodology, data discussion. MHRF: experimental operation. GAA: methodology, data discussion.
RFA: data discussion. EML: data curation, statistics, data discussion, writing - review & editing.

Availability of data and materials:

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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