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RESEARCH ARTICLE

Mineral and organo-mineral fertilization alters soil Ca–Mg–K balance and base saturation during early coffee establishment

[version 1; peer review: 2 approved with reservations]

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Abstract

Exchangeable-cation ratios and cation exchange capacity indices can capture early shifts in soil base-cation balance during coffee establishment. We assessed calcium (Ca), magnesium (Mg) and potassium (K) balance in a newly established Arabica coffee field (Coffea arabica L., cultivar Acaiá IAC 474-19) in Indianópolis, Minas Gerais, Brazil, on a clayey dystrophic Red Latosol, comparable to a Ferralsol and an Oxisol. A randomized complete block 3 × 4 factorial compared planting fertiliser sources, mineral fertiliser (MIN, 11-52-00), poultry-manure organo-mineral fertiliser (OMF-CF, 06-30-00) and filter-cake organo-mineral fertiliser (OMF-TF, 06-30-00), combined with four rates of a poultry-based organic fertiliser (2, 4, 6 and 8 t ha?[1]), with four blocks. Treatments were applied once in the planting furrow (Day 0), seedlings were transplanted on Day 40, and soil (0–20 cm) was sampled 90 days after transplanting (Day 130); pre-application samples provided site characterisation. Exchangeable Ca, Mg and K and potential acidity (hydrogen plus aluminium, H+Al) were used to compute cation ratios and proportions relative to cation exchange capacity at pH 7.0 (T), including base saturation (V). Factorial analysis of variance with Tukey's HSD ($p \leq 0.05$) showed Source × Rate interactions for nine of ten indicators; K/T showed no interaction. Relative to the site baseline (V 58%, Ca/T 40%, H+Al/T 42%), all treatments increased V at Day 130 (66–77%) and reduced H+Al/T (23–34%). OMF-CF at 8 t ha–1 achieved the highest V (77%) and Ca/T (66%) and the lowest H+Al/T (23%), but also the highest Ca/Mg (7.1) and Ca/K (37), indicating potential cation-imbalance risk. OMF-TF

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responses were limited across rates (V 71–75%), whereas MIN showed non-monotonic patterns. Baseline values were not plot-specific; inference is based on among-treatment comparisons at Day 130.

Keywords
Exchangeable cations, Cation exchange capacity, Cation ratios, Poultry manure, Filter cake, Ferralsol, Oxisol, Red Latosol

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Introduction

Establishing arabica coffee (*Coffea arabica* L.) requires soils with controlled acidity and adequate supplies of exchangeable base cations, because soil acidity simultaneously reduces Ca, Mg, and K availability and increases aluminium (Al) in phytotoxic forms (Quispe *et al.*, 2025). In coffee-growing areas, soil pH, exchangeable bases, Al, potential acidity (hydrogen plus aluminium, H+Al), cation exchange capacity (CEC), and base saturation have been used to describe the soil chemical environment and its response to management practices (Alvarenga *et al.*, 2023). However, standard acidity indicators such as pH and base saturation may not fully capture competitive interactions among base cations during the critical establishment phase, when fertiliser inputs can rapidly shift cation proportions on exchange sites without proportional changes in total CEC (Alvarenga *et al.*, 2023).

The balance among Ca, Mg, and K can be evaluated using cation ratios and proportions normalised to cation exchange capacity. In this study, cation exchange capacity estimated at pH 7.0 is denoted as T. and is used to express the relative occupancy of exchange sites by base cations and acidity. These indices integrate competition for exchange sites and nutrient uptake processes, complementing pH and base saturation by capturing fertiliser-driven shifts in cation proportions over short periods even when total exchange capacity changes little (Antonangelo *et al.*, 2024). Experimental evidence from greenhouse tomato seedlings demonstrates that balancing Ca, Mg, and K proportions relative to cation exchange capacity can reduce ionic competition and improve seedling growth (Yang *et al.*, 2024).

Organo-mineral fertilisers (OMF) combine an organic matrix with mineral sources to synchronise nutrient release with crop demand, potentially reducing nutrient losses and improving nutrient-use efficiency relative to sole mineral fertilisation (Li *et al.*, 2022). In coffee systems, field evidence has reported comparable short-term vegetative growth under organo-mineral and mineral fertilisers, despite differences in nutrient-release dynamics and soil chemical responses (da Mota *et al.*, 2025). This apparent similarity in early growth reinforces the need to monitor soil chemical indicators of cation balance during establishment, when fertiliser-induced shifts in exchange-site occupancy can occur before measurable plant responses and may influence nutrient uptake and longer-term stand development.

Organic matrices used in organo-mineral formulations differ in nutrient composition and reactivity, which can translate into distinct short-term effects on exchangeable cation balance. Poultry-derived materials can increase soil organic matter and supply nitrogen (N), phosphorus (P) and potassium (K), supporting measurable shifts in base-cation availability after application (Thepsilvisut *et al.*, 2022). Filter cake, a by-product of the sugarcane industry, is typically rich in organic matter and P and is used as a soil amendment; nutrient release is governed by mineralisation and may reduce reliance on mineral fertilisers (de Soares *et al.*, 2024).

Despite the widespread use of organo-mineral fertilisers in Brazilian coffee systems, short-term effects on soil Ca–Mg–K balance during establishment remain insufficiently characterised. In particular, it is unclear whether responses to organic-fertiliser rate differ among planting-fertiliser sources and whether cation ratios and cation exchange capacity (CEC)-based indices are sensitive enough to detect treatment effects within 90 days after transplanting, when soil chemical shifts may precede clear plant responses. We therefore tested the hypotheses that (i) organic-rate effects on cation balance depend on planting-fertiliser source (Source × Rate interaction), consistent with differences in nutrient-release dynamics and matrix reactivity, and (ii) CEC-normalised proportions and cation ratios capture early redistribution of cations on exchange sites. To address these questions, we evaluated exchangeable cation ratios and CEC at pH 7.0 (T)-based proportions at 90 days after transplanting in a factorial field trial comparing mineral and organo-mineral planting fertilisers combined with increasing organic-fertiliser rates.

Methods and materials

The experiment was carried out from October 2022 to January 2023 in the study area located at Fazenda Furnas, Indianópolis, Minas Gerais, Brazil (18°56'04.9" S; 47°56'08.3" W; 911 m a.s.l.). The Köppen–Geiger climate classification is Aw, characterised by a rainy summer and a dry winter. To contextualise weather conditions relevant to nutrient dynamics and organic-matter mineralisation during the experimental window, climatological data for Indianópolis indicate a mean annual temperature of 22.1 °C and annual precipitation of 1409 mm. From October to January, mean monthly air temperature ranges from 22.8 to 24.2 °C, and monthly rainfall ranges from 113 to 267 mm, totalling 832 mm over the period (October 113 mm, November 204 mm, December 267 mm, January 248 mm) (Climate-Data.org, n.d.). The location of the experimental area is shown in Figure 1.

The soil was classified as a clayey dystrophic Red Latosol (Embrapa, 2018). Baseline characterisation was conducted before treatment assignment and fertiliser application at 0–20 cm and 20–40 cm. Because sampling preceded randomization, subsamples were collected from the areas that later formed the experimental plots and pooled by planned treatment assignment to produce one composite sample per treatment at each depth (12 composite samples per depth). These baseline values therefore describe initial site conditions rather than plot-specific pre-treatment measurements; baseline-to-90-day contrasts indicate temporal shifts but do not test treatment effects over time. Treatment effects were evaluated using plot-level measurements collected at 90 days after transplanting. Baseline properties are reported in Table 1a–d.

The plant material was Arabica coffee (*Coffea arabica* L.), cultivar Acaiá IAC 474-19. This cultivar was chosen due to its widespread use in Minas Gerais and its suitability for row-based systems compatible with mechanised operations and harvesting (Fundação Procafé). The field was established in October 2022 after disc harrowing to 25 cm, using a 3.8 m × 0.6 m

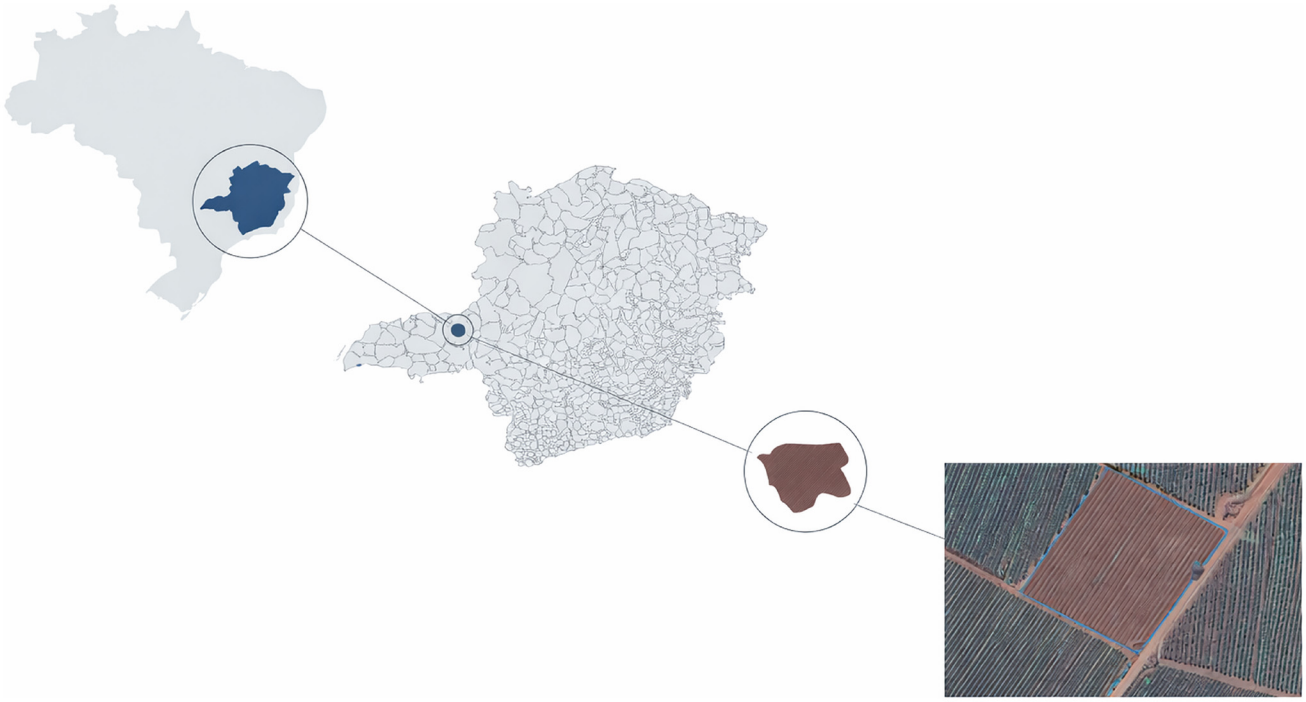

Figure 1. Location map of the experimental area in Indianópolis, Minas Gerais, Brazil. Note: Geographical location of the experimental site in Indianópolis, Minas Gerais, Brazil, including national, state, and local context.

Table 1. Baseline soil physical and chemical properties before fertiliser application at two depths, based on treatment-level composite samples.
Table 1a. Particle-size distribution, pH, and available nutrients.

Physical and chemical soil properties								
Depth	Sand	Silt	Clay	pH	P (Mehlich-1)	P (resin)	K^+	$S\text{-}SO_4^{2-}$
cm	g Kg^{-1}			H_2O	mg dm^{-3}			
0-20	321	191	488	5,5	17,1	55,2	131	36
20-40	412	220	368	5,8	9,5	53,0	90	25

Table 1b. Exchangeable cations, organic fractions, and cation exchange capacity.

Depth	K	Ca^{+2}	Mg^{+2}	Al^{3+}	H+Al	Organic matter	Organic C	SB	t	T
cm	cmolc dm^{-3}					g kg^{-1}		cmolc dm^{-3}		
0-20	0,3	4,0	1,5	0,0	4,2	3,2	1,9	5,8	5,8	10,0
20-40	0,2	3,2	1,1	0,0	3,8	0,9	1,0	4,5	4,5	8,3

Note: Organic matter and organic C were converted from dag kg^{-1} to g kg^{-1} by multiplying by 10.

Table 1c. Micronutrients.

Depth (cm)	B	Cu	Fe	Mn	Zn
cm	mg dm⁻³				
0–20	0.6	5.2	31.0	2.5	2.8
20–40	0.5	4.5	28.0	2.0	2.2

Table 1d. Proportions of cations and acidity relative to T.

Depth	Ca/T	Mg/T	K/T	H+Al/T	(Ca+Mg)/T	Base saturation, V
cm	%					
0–20	40	15	3	42	55	58
20–40	38	13	2	45	51	54

Note: Baseline values are site characterisation prior to treatment assignment (12 treatment-level composite samples per depth; one composite per planned treatment formed by pooling the four blocks); treatment inference is based on plot-level comparisons at 90 days. Methods: sand/silt/clay, pipette (slow agitation); pH, water; P and K, Mehlich-1 (0.05 mol L^{-1} HCl + 0.0125 mol L^{-1} H_2SO_4); P (resin), anion-exchange resin (reported alongside Mehlich-1 for interpretability, not method comparison); SO_4–S, monocalcium phosphate (Ca = 0.00125 mol L^{-1}); exchangeable Ca^{2+}, Mg^{2+} and Al^{3+}, 1 mol L^{-1} KCl; H+Al, SMP buffer (pH 7.5); B, hot $BaCl_2{\cdot}2H_2O$ (0.0125%); Cu, Fe, Mn and Zn, DTPA–TEA–$CaCl_2$ (0.005 mol L^{-1} DTPA + 0.1 mol L^{-1} TEA + 0.01 mol L^{-1} $CaCl_2$, pH 7.3). SB = Ca+Mg+K; t = effective cation exchange capacity; T = cation exchange capacity at pH 7.0; V = base saturation. Units as in headings. Methods followed Embrapa (1997)

spacing (4,385 plants ha^{-1}). Seedlings were approximately 5–6 months old at transplanting, produced in 120 mL tubes with a coconut-fibre-based substrate, and transplanted in the early rainy season to promote establishment. Each plot comprised eight plants arranged in a single row; based on the planting spacing, plot dimensions were approximately 3.8 m × 4.2 m (≈16 m^2). The four central plants were designated as the assessment area, and the two plants at each end served as within-plot buffers.

The experiment followed a randomized complete block design in a 3 × 4 factorial arrangement, totalling 12 treatments with four blocks (48 plots). The planting-fertiliser source factor comprised a mineral fertiliser (11-52-00) and two organo-mineral fertilisers (OMF; 06-30-00), one based on a poultry-manure organic matrix and the other based on a filter-cake organic matrix. The organic-rate factor consisted of 2, 4, 6 and 8 t ha^{-1} of a poultry-based organic fertiliser. Lime (3 t ha^{-1}) and coffee straw mulch (4 L m^{-2}) were applied before treatment application. All treatments were applied once in the planting furrow (Day 0). Coffee seedlings were transplanted 40 days after fertiliser application (Day 40). Soil sampling was performed 90 days after transplanting (130 days after fertiliser application; Day 130). Field operations and the sampling position are shown in Figure 2a–c.

Figure 2 summarises key field operations and the standardised sampling position adopted to support reproducibility. Soil was sampled with a soil auger at 0–20 cm along the planting row. Within each plot, subsamples were collected at evenly spaced points between the four central plants, 5–8 cm from the stem under the drip irrigation line, pooled into one composite sample, and processed by air-drying, 2-mm sieving, and storage in sealed bags until chemical analysis.

The declared nutrient composition of the fertilisers used in the treatments is shown in Table 2.

Table 2 shows the higher P_2O_5 content of the mineral fertiliser (11-52-00). Among organo-mineral fertilisers, OMF-CF includes declared S, B and Zn, whereas OMF-TF declares only N and P_2O_5. The poultry-based organic fertiliser declares K_2O, Ca and Mg in addition to N and P_2O_5. The chemical composition of the organic matrices used in the fertiliser formulations is presented in Table 3a–b.

Table 3 shows the high moisture content of filter cake, which affects handling, storage, and field application when rates are expressed on a fresh-weight basis. Poultry waste presented the highest water-soluble K_2O content.



Figure 2. Field operations and soil sampling during early coffee establishment. (a) Fertilisers applied in the planting furrow (Day 0). (b) Field view at soil sampling, 90 days after transplanting (130 days after fertiliser application), with plot labels. (c) Sampling position beneath the drip line at the 90-day assessment (130 days after fertiliser application).

Table 2. Declared fertiliser composition (%), according to the manufacturer's label.

Fertiliser	N	P_2O_5	K_2O	Ca	Mg	S	B	Zn
Mineral 11-52-00	11,0	52,0	–	–	–	–	–	–
OMF-CF 06-30-00	6,0	30,0	–	–	–	3,0	0,2	0,1
OMF-TF 06-30-00	6,0	30,0	–	–	–	–	–	–
Poultry-based organic fertiliser	1,5	2,5	0,8	4,0	1,0	1,0	–	–

Note: Values are expressed as mass percentage (%). "–" indicates not declared on the manufacturer's label. Abbreviations: OMF: organo-mineral fertiliser; OMF-CF: poultry-manure organo-mineral fertiliser (planting); OMF-TF: filter-cake organo-mineral fertiliser (planting).

Table 3. Chemical composition of the organic matrices used in the fertiliser formulations (fresh basis).
Table 3a. Reaction, moisture, and C:N ratio.

Organic matrix	pH (H_2O, 1:2.5 v/v)	Moisture %	C:N
Poultry litter	8.0	25.0	10.1:1
Filter cake	7.5	70.0	11.0:1
Poultry waste	7.3	20.0	6.4:1

Table 3b. Carbon and nutrient composition.

Organic matrix	Total organic carbon, TOC	Total N	Total P_2O_5	Water-soluble K_2O
	g kg^{-1}			
Poultry litter	337.5	33.5	38.5	8.8
Filter cake	296.0	27.0	33.4	<LQ
Poultry waste	285.0	44.4	21.5	67.5

Note (methods and abbreviations): Poultry litter was the organic matrix used in the organo-mineral fertiliser, whereas poultry waste was used in the organic fertiliser. pH was measured in an aqueous suspension (1:2.5, v/v). Moisture was determined gravimetrically after oven-drying at 65 °C to constant weight. The C:N ratio was calculated from total organic carbon (TOC) determined by dry combustion and total nitrogen determined by sulfuric digestion followed by UV–Vis spectrophotometry. Total P_2O_5 was determined after nitric–perchloric digestion and quantified by atomic absorption spectrophotometry. Water-soluble K_2O was extracted with water and quantified by flame emission spectrophotometry. LQ = limit of quantification (range 0.1–67%). Methods followed MAPA (2017); AOAC (2007).

Baseline soil characterisation was performed before fertiliser application, and treatment effects were assessed using plot-level samples collected 90 days after transplanting. The 90-day interval was adopted to capture early fertiliser-induced soil chemical changes during coffee establishment (Afrizal *et al.*, 2023). Soil chemical analyses were conducted at Safrar Análises Agrícolas (Uberlândia, Minas Gerais) following standard Brazilian soil-testing procedures (Embrapa, 1997), as implemented by the laboratory and supported by routine analytical procedures widely used in agricultural laboratories (Bataglia *et al.*, 1983). Exchangeable Ca^{2+}, Mg^{2+} and Al^{3+} were extracted with 1 mol L^{-1} KCl and quantified by atomic absorption spectrometry, whereas P and K were extracted with Mehlich-1 and quantified by colorimetry (P) and flame photometry (K). Potential acidity (H+Al) was estimated using the SMP buffer (pH 7.5). From the measured values, sum of bases (SB), effective cation exchange capacity (t), and cation exchange capacity at pH 7.0 (T) were obtained, and cation ratios and T-based proportions, including base saturation (V), were calculated as described in Embrapa (1997). Exchangeable Na was not reported by the laboratory; therefore, Na/T was not calculated.

Data were analysed by factorial analysis of variance (ANOVA) for a 3 × 4 factorial arrangement in a randomized complete block design, using Python 3.11.2 and the statsmodels package (v0.14.3). When significant effects were detected, means were compared using Tukey's HSD test ($p \leq 0.05$).

Results

Soil samples collected 90 days after transplanting (0–20 cm) were analysed for exchangeable Ca, Mg and K and potential acidity (H+Al), and the derived cation ratios and cation exchange capacity (CEC)-based proportions were calculated. The effects of fertiliser source, organic rate, and the source × rate interaction are summarised in Table 4.

Factorial ANOVA (Table 4) indicated significant Source × Rate interactions ($p \leq 0.05$) for nine of ten indicators; K/T was the only indicator without interaction ($p = 0.088$). The main effect of Source was not significant for any indicator (all $p > 0.05$), while the main effect of Rate was significant only for Mg/T ($p = 0.043$). Overall, the predominance of interactions indicates that organic-rate effects depended on the planting-fertiliser source, supporting interpretation within each source across rates. Coefficients of variation ranged from 6.6% to 17.7%.

Treatment means for exchangeable cation ratios at 90 days are presented in Table 5.

Relative to baseline site characterisation, all 90-day treatments showed higher cation ratios, with Ca/Mg ranging from 4.18 to 7.22 and Ca/K from 23.62 to 36.95 across source–rate combinations. Patterns differed by source: under OM-CF, Ca/Mg and (Ca+Mg)/K increased overall with rate, whereas under MIN the highest Ca/Mg occurred at an intermediate rate (4 t ha^{-1}). OM-TF showed comparatively narrower variation across rates for Ca/K and Mg/K. These source-dependent patterns are consistent with the interaction effects in Table 4.

CEC-based proportions and base saturation at 90 days are presented in Table 6.

Across source–rate combinations, Ca/T increased from a baseline of 40% to 52.91–66.17% at 90 days, while H+Al/T declined from 42% to 22.64–34.00%, indicating a lower relative contribution of potential acidity within the exchange complex. Base

Table 4. Analysis of variance for soil chemical criteria at 90 days after transplanting (130 days after fertiliser application) (0–20 cm).

Indicator	p(Source)	p(Rate)	p(Source×Rate)	CV (%)
Ca/Mg	0.131ns	0.174ns	0.003**	17.7
Ca/K	0.433ns	0.067ns	0.021*	17.1
Mg/K	0.240ns	0.165ns	0.010**	14.9
(Ca+Mg)/K	0.482ns	0.073ns	0.035*	15.8
Ca/T	0.144ns	0.329ns	0.004**	8.2
Mg/T	0.128ns	0.043*	0.008**	11.2
K/T	0.243ns	0.146ns	0.088ns	13.9
H+Al/T	0.312ns	0.436ns	0.030*	17.0
(Ca+Mg)/T	0.321ns	0.388ns	0.030*	6.9
V	0.309ns	0.418ns	0.029*	6.6

Note: Randomized complete block design, 3 × 4 factorial. p-values from the F-test: ns ($p > 0.05$), * ($p \leq 0.05$), ** ($p \leq 0.01$). Tukey's HSD at 5% when applicable. CV = coefficient of variation. Abbreviations: OMF-CF, poultry-manure organo-mineral fertiliser (planting); OMF-TF, filter-cake organo-mineral fertiliser (planting); MIN, mineral fertiliser (planting); Rate, poultry-based organic fertiliser rate (t ha^{-1}).

Table 5. Exchangeable cation ratios in the soil at 90 days after transplanting (130 days after fertiliser application) (0–20 cm), by fertiliser source and organic fertiliser rate.

Indicator	Rate (t ha^{-1})	OM-CF	OM-TF	MIN
Ca/Mg	Baseline	2.70	2.70	2.70
Ca/Mg	2	4.18 (0.28)	6.73 (0.60)	5.35 (0.35)
	4	5.47 (0.71)	6.08 (0.77)	7.22 (1.10)
	6	5.42 (0.37)	6.35 (0.46)	4.90 (0.23)
	8	7.10 (0.40)	5.85 (0.29)	5.15 (0.10)
Ca/K	Baseline	11.80	11.80	11.80
Ca/K	2	26.23 (3.38)	30.22 (2.81)	26.65 (1.74)
	4	23.62 (2.54)	30.48 (1.91)	34.38 (3.35)
	6	26.48 (3.80)	32.35 (2.85)	26.38 (1.75)
	8	36.95 (3.05)	29.02 (2.74)	33.15 (1.39)
Mg/K	Baseline	4.40	4.40	4.40
Mg/K	2	6.28 (0.69)	4.55 (0.48)	5.03 (0.43)
	4	4.33 (0.09)	5.25 (0.72)	4.90 (0.40)
	6	4.85 (0.64)	5.15 (0.47)	5.38 (0.25)
	8	5.20 (0.33)	4.95 (0.31)	6.47 (0.29)
Ca+Mg/K	Baseline	16.20	16.20	16.20

Note: Values are mean (SE), n = 4 blocks (SE = SD/√n). Abbreviations: OMF-CF, poultry-manure organo-mineral fertiliser (planting); OMF-TF, filter-cake organo-mineral fertiliser (planting); MIN, mineral fertiliser (planting); Rate, poultry-based organic fertiliser rate (t ha^{-1}). Baseline values (Table 1; 0–20 cm) are site characterisation data for context. Ratios were calculated from exchangeable Ca, Mg and K (cmolc dm^{-3}).

Table 6. CEC at pH 7.0 (T)-based proportions and soil base saturation at 90 days after transplanting (130 days after fertiliser application) (0–20 cm), by fertiliser source and organic fertiliser rate.

Indicator	Rate (t ha^{-1})	OM-CF	OM-TF	MIN
Ca/T (%)	Baseline	40.00	40.00	40.00
Ca/T (%)	2	52.91 (2.18)	63.47 (1.34)	57.20 (0.84)
	4	53.86 (6.01)	59.23 (1.24)	63.37 (1.92)
	6	60.09 (3.40)	61.02 (1.70)	55.44 (2.22)
	8	66.17 (1.20)	61.22 (0.58)	56.85 (0.85)
Mg/T (%)	Baseline	15.00	15.00	15.00
Mg/T (%)	2	12.81 (0.58)	9.60 (0.68)	10.86 (0.73)
	4	9.87 (0.51)	10.09 (0.93)	9.23 (1.06)
	6	11.13 (0.46)	9.73 (0.46)	11.37 (0.19)
	8	9.38 (0.46)	10.51 (0.49)	11.11 (0.34)
K/T (%)	Baseline	3.00	3.00	3.00
K/T (%)	2	2.09 (0.20)	2.16 (0.20)	2.17 (0.10)
	4	2.28 (0.11)	1.97 (0.13)	1.89 (0.15)
	6	2.40 (0.30)	1.93 (0.15)	2.12 (0.12)
	8	1.82 (0.11)	2.17 (0.19)	1.72 (0.09)
H+Al/T (%)	Baseline	42.00	42.00	42.00
H+Al/T (%)	2	32.18 (1.94)	24.77 (1.16)	29.77 (1.13)
	4	34.00 (6.07)	28.71 (0.43)	25.52 (1.36)
	6	26.38 (3.30)	27.32 (1.22)	31.07 (2.18)
	8	22.64 (1.12)	26.11 (0.98)	30.32 (1.22)
(Ca+Mg)/T (%)	Baseline	55.00	55.00	55.00
(Ca+Mg)/T (%)	2	65.73 (2.12)	73.08 (1.21)	68.07 (1.20)
	4	63.72 (6.02)	69.32 (0.50)	72.59 (1.43)
	6	71.22 (3.49)	70.75 (1.29)	66.81 (2.17)
	8	75.54 (1.19)	71.73 (0.88)	67.96 (1.15)
V (%)	Baseline	58.00	58.00	58.00
V (%)	2	67.75 (2.02)	75.25 (1.11)	70.50 (1.19)
	4	66.00 (5.94)	71.00 (0.41)	74.25 (1.31)
	6	73.50 (3.30)	72.50 (1.19)	68.75 (2.25)
	8	77.25 (1.11)	74.00 (0.91)	69.50 (1.26)

Note: Values are mean (SE), n = 4 blocks (SE = SD/√n). Abbreviations: OMF-CF, poultry-manure organo-mineral fertiliser (planting); OMF-TF, filter-cake organo-mineral fertiliser (planting); MIN, mineral fertiliser (planting); Rate, poultry-based organic fertiliser rate (t ha^{-1}). Baseline values (Table 1; 0–20 cm) are site characterisation data for context. T = cation exchange capacity at pH 7.0. Proportions are expressed as % of T. V = base saturation.

saturation (V) increased from 58% at baseline to 66.00–77.25% at 90 days (i.e., +8 to +19 percentage points). In contrast, K/T remained within a narrow interval (1.72–2.40%), consistent with the non-significant interaction for this indicator in Table 4. Because baseline values derive from site characterisation rather than plot-level measurements, baseline-to-90-day comparisons are descriptive; statistical inference in this study is based on between-treatment comparisons at 90 days. Post-hoc comparisons (Table 7) revealed limited pairwise differentiation within sources for most indicators, indicating that the significant Source × Rate interactions reflect complex redistributions across the factorial structure rather than monotonic rate responses within individual sources.

Table 7. Tukey's HSD grouping letters for means at 90 days after transplanting (130 days after fertiliser application) across organic rates within each planting-fertiliser source ($p \leq 0.05$).

Indicator	Rate (t ha^{-1})	OM-CF	OM-TF	MIN
Ca/Mg	2	b	a	a
	4	ab	a	a
	6	ab	a	a
	8	a	a	a
Ca/K	2	a	a	a
	4	a	a	a
	6	a	a	a
	8	a	a	a
Mg/K	2	a	a	ab
	4	a	a	b
	6	a	a	ab
	8	a	a	a
Ca+Mg/K	2	a	a	a
	4	a	a	a
	6	a	a	a
	8	a	a	a
Ca/T (%)	2	a	a	ab
	4	a	a	a
	6	a	a	b
	8	a	a	ab
Mg/T (%)	2	a	a	a
	4	b	a	a
	6	ab	a	a
	8	b	a	a
K/T (%)	2	a	a	a
	4	a	a	a
	6	a	a	a
	8	a	a	a
H+Al/T (%)	2	a	a	a
	4	a	a	a
	6	a	a	a
	8	a	a	a
Ca+Mg/T (%)	2	a	a	a
	4	a	a	a
	6	a	a	a
	8	a	a	a
V (%)	2	a	a	a
	4	a	b	a
	6	a	ab	a
	8	a	ab	a

Note: Within each indicator and planting-fertiliser source, organic-rate means followed by different letters differ by Tukey's HSD ($p \leq 0.05$). Abbreviations: OMF-CF, poultry-manure organo-mineral fertiliser (planting); OMF-TF, filter-cake organo-mineral fertiliser (planting); MIN, mineral fertiliser (planting); Rate, poultry-based organic fertiliser rate (t ha^{-1}). Comparisons were performed across rates within each source using plot-level values (n = 4 per mean).

Discussion

Short-term soil chemical responses during coffee establishment were driven by Source × Rate interactions for most criteria, indicating that the effect of organic-fertiliser rate depended on the planting-fertiliser source (Table 4). Relative to the site baseline (Table 1), by 90 days after transplanting (130 days after fertiliser application) there was a general shift towards greater base-cation occupancy of the exchange complex, with base saturation increasing from 58% to 66–77% and Ca/T from 40% to 53–66%, while H+Al/T decreased from 42% to 23–34% (Table 6). Because baseline values were derived from treatment-level composite samples for site characterisation rather than plot-specific baselines, these contrasts describe temporal shifts and should be interpreted separately from the statistical comparisons among treatments at 90 days.

The experimental period coincided with the onset of the rainy season in Indianópolis. Climatological records indicate mean monthly temperatures of 22.8–24.2 °C and rainfall of 113–267 mm from October to January, totalling 832 mm over the period (Climate-Data.org, n.d.). Under these warm and wet conditions, microbial activity and organic-matter mineralisation

tend to intensify, which can accelerate nutrient release and exchange-site redistribution over short time frames, particularly for poultry-derived matrices with relatively low C:N ratios (6.4–10.1:1; Table 3). Incubation evidence also supports interactive temperature–moisture controls on mineralisation and priming, consistent with measurable changes in CEC-normalised indicators within the timeframe evaluated (He *et al.*, 2024).

The poultry-manure organo-mineral fertiliser (OMF-CF) at the highest organic rate (8 t ha^{-1}) produced the strongest shift in exchange-site occupancy, with the highest V (77%) and Ca/T (66%) and the lowest H+Al/T (23%) (Table 6). This pattern is consistent with organo-mineral mechanisms in which matrix reactivity and nutrient-release synchrony influence early soil chemical reactions and base-cation distribution, and with field evidence that poultry-based inputs can increase soil chemical fertility metrics (Agbede, 2025; de Benites *et al.*, 2022; Uddin *et al.*, 2025). In this Cerrado Oxisol/Ferralsol context, the results indicate that poultry-based OMF at high rates can rapidly increase the relative share of bases in the exchange complex during establishment.

Practical implications for coffee establishment

At the same time, the same source–rate combination yielded the highest Ca/Mg (7.1) and Ca/K (37) ratios (Table 5), confirming that higher base saturation can coincide with shifts in Ca–Mg–K balance. Calcium can dominate exchange sites and reduce Mg and K competitiveness during uptake, which is critical during establishment when root systems are still developing (Antonangelo *et al.*, 2024). Magnesium supports chlorophyll formation, enzyme activation and energy transfer, and deficiencies are often associated with antagonistic cation relationships in fertilised systems (Ishfaq *et al.*, 2022; Dölger *et al.*, 2024). In practice, high poultry-based OMF-CF rates should not be evaluated by base saturation alone; soil monitoring should include cation ratios and T-based proportions, and foliar diagnosis at 6–12 months can help detect emerging Mg or K limitations before growth or yield penalties occur (Dölger *et al.*, 2024).

Operational feasibility should also be considered. The 8 t ha^{-1} rate may impose logistical and cost constraints, including transport, handling and uniform placement of bulky materials. Therefore, the chemical gains observed at this rate should be interpreted alongside field practicality and whole-farm nutrient planning, particularly where applications are repeated across seasons.

In contrast, the filter-cake organo-mineral fertiliser (OMF-TF) showed limited variation across organic rates, with V = 71–75% (Table 6). This muted short-term response is consistent with the high moisture content of filter cake (70%, Table 3), which lowers dry-matter input when rates are expressed on a fresh-weight basis. For the same nominal rate, filter cake supplied ~2.7-fold less dry matter than poultry waste (30% vs. 80% dry matter), which likely diluted early chemical effects. Given that filter cake is primarily valued as a source of organic matter and P, responses are expected to depend on composition, processing and mineralisation kinetics (Soares *et al.*, 2024; Uddin *et al.*, 2025). For meaningful comparisons among matrices, future trials should standardise organic amendment rates on a dry-weight basis and report moisture content.

Mineral planting fertilisation produced non-monotonic patterns in several indicators, with peaks at intermediate organic rates (Table 5–Table 6). This behaviour is consistent with mixed-source nutrient dynamics, where soluble mineral inputs can shift early exchange equilibria while organic inputs mineralise over time, and short-term CEC-based indicators reflect redistribution rather than a simple dose response. Reviews of organo-mineral performance similarly emphasise the role of matrix reactivity, release synchrony and soil buffering capacity in shaping response patterns (Uddin *et al.*, 2025).

Finally, microbiological and safety aspects become more relevant where poultry-derived matrices are used repeatedly. Field evidence indicates that poultry litter can alter soil bacterial community composition alongside changes in chemical attributes (Sant'Anna *et al.*, 2024). Other studies report that manure application rate can influence the distribution of antibiotic resistance genes and that long-term manure inputs may increase cadmium accumulation risk depending on dose, duration and soil conditions (Tang *et al.*, 2024; Wang *et al.*, 2024). These findings support sanitation control of organic matrices and monitoring strategies that extend beyond fertility where manure-derived materials are applied recurrently.

Regulatory and cross-regional context

In Brazil, fertilisers and related inputs are regulated under Law No. 6,894/1980 and its implementing Decree No. 4,954/2004 (BRASIL, 1980; BRASIL, 2004). Regulatory frameworks shape how organo-mineral fertilisers (OMF) are defined, marketed and constrained across regions. In the European Union, Regulation (EU) 2019/1009 establishes requirements for EU fertilising products, including safety criteria and limits for contaminants and pathogens, as well as conformity assessment for CE-marked products (European Union, 2019). In addition, manure-derived inputs are restricted in nitrate vulnerable zones under the Nitrates Directive framework, which sets an annual ceiling of 170 kg N ha^{-1} from manure, with derogations under specific conditions (European Union, 1991; European Commission, n.d.). These rules do not change the soil-chemical mechanisms observed here, but they affect how poultry-based OMF and application rates would be justified and managed in European production systems, particularly where soils are Ca-rich and nutrient loading is constrained by environmental compliance.

Cross-regional comparison also requires analytical caution. Laboratory methods used to estimate CEC and base saturation vary among countries and testing systems, which can shift CEC-normalised percentages and complicate direct comparison of Ca/T, Mg/T and V across studies. Harmonisation work

shows that method choice can alter CEC–base saturation relationships, supporting interpretation based on within-method contrasts rather than assuming absolute equivalence across protocols (Kabala & Jedrzejewski, 2024). Clear reporting of extractants, CEC estimation and calculation rules therefore remains essential for international interpretability.

Methodological considerations and limitations

The main contribution of this field trial is to show that CEC-based indicators and cation ratios can differentiate treatments within 90 days after transplanting and reveal trade-offs between increasing base saturation and maintaining Ca–Mg–K balance. However, generalisation is constrained by the single-site, single-season design and by limited power for some pairwise contrasts (four blocks across 12 treatments). Replication across contrasting soils and climatic conditions, and across multiple seasons, is needed to determine whether the observed patterns persist beyond establishment and to support robust management recommendations.

Future work would benefit from: (i) collecting plot-level baselines to separate time and treatment effects; (ii) adding repeated sampling dates (e.g., 30, 90, 180 and 360 days) to quantify response kinetics; (iii) standardising organic inputs on a dry-weight basis and reporting moisture; (iv) reporting cation inputs as kg ha^{-1} of Ca, Mg and K; (v) integrating foliar diagnosis and longer-term growth and yield metrics; and (vi) including targeted microbiological and contaminant indicators where manure-derived matrices are applied repeatedly (Uddin *et al.*, 2025).

Conclusions

Exchangeable cation ratios and T-based proportions sensitively captured early soil chemical shifts during coffee establishment. Source × Rate interactions for nine of ten indicators show that organic-rate effects depend on the planting fertilizer source. The poultry-based organo-mineral fertilizer at planting (OMF-CF) at 8 t ha^{-1} reached the highest V (77%) and Ca/T (66%) and the lowest H+Al/T (23%), but also the highest Ca/Mg (7.1) and Ca/K (37), indicating that gains in base saturation can coincide with Ca–Mg–K imbalance and potential antagonism risk. In practice, high OMF-CF rates should be accompanied by soil monitoring of cation ratios during establishment and foliar diagnosis at 6–12 months. The filter-cake-based organo-mineral fertilizer at planting (OMF-TF) showed limited variation across rates (V= 71–75%), consistent with its high moisture and lower dry-matter input on a fresh-weight basis; future work should standardize organic amendments on a dry-weight basis. Mineral planting fertilization (MIN) produced non-monotonic responses, reinforcing the need for indicator-based diagnostics rather than assuming linear dose effects.

Ethics and consent

Ethical approval and consent were not required.

Data availability

Zenodo: Data repository for "Mineral and organo-mineral fertilisation alters soil Ca–Mg–K balance and base saturation during early coffee establishment". DOI: https://doi.org/10.5281/zenodo.18200463 (Diniz *et al.*, 2026; Henrique dos Santos Diniz (2026)).

This record contains the underlying datasets required to reproduce all analyses and tables reported in the article, including: plot_level_data_90d.csv (plot-level soil dataset at 90 days after transplanting, 0–20 cm; 12 treatments × 4 blocks); supplementary_statistical_analysis_outputs.xlsx (ANOVA outputs for Table 4; means and standard errors used in Table 5–Table 6; Tukey HSD outputs for Table 7; full pairwise Tukey results); baseline_site_characterization_table1.csv (baseline site characterisation values reported in Table 1); Final chemical analysis – Data analyzed.xlsx (laboratory dataset used to generate the 90-day plot-level indicators and summaries); and Initial soil analysis.jpeg (baseline laboratory report used for site characterisation). Data are available under the terms of the Creative Commons Attribution 4.0 International licence (CC BY 4.0), as indicated in LICENSE_CC_BY_4.0_revised.txt.

Extended data

The Zenodo record also includes the figure and image files supporting the methods and field layout (e.g., Fig 1. Location.png, Figure2_field_operations_and_sampling.tiff, Fig2a.png, Fig2b.png, Fig2c.png).

Software availability

Reproducible analysis code is provided in the Zenodo record (statistical_analysis_reproducible_from_csv.py), which reads the plot-level dataset and regenerates the ANOVA and Tukey HSD outputs used in the manuscript.

Source code: https://github.com/mateussdiniz1-sys/coffee-soil-cation-balance-analysis

Archived software (all versions): https://doi.org/10.5281/zenodo.18208472

License: MIT License

Acknowledgements

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?

Srdjan Seremesic
University of Novi Sad, Novi Sad, Serbia

Respected Editor and dear Authors
Thank you for the opportunity to evaluate the submitted text for Open Research Europe collection. The chosen topic is relevant and current, and the presented data on this topic are not numerous and fully available in the selected region. However, the manuscript could benefit from better contextualization of cation ratio theory and stronger theoretical positioning presenting some guidelines and solutions that more practical.
The introduction provides a general overview of the selected topic and partially address or emphasise specific aspects of the treatments investigated for tropical soils or coffee, or the location of the experiment. It should carefully position the space where manuscript could contribute to the chosen research problem. This section also covers the methodology (90 days of study). Therefore, there is no need to present the experimental idea and rationale. The reasons why the author decided to conduct research over a short period could also be included in this section.
Regarding the methodological approach to this study soil samples before the experimental set up was takan as composoite (bulk) samples (is number repetition sufficient to plot size) and not specific to some plots which may latter mask the experimental results and cause lack of temporal comparision. Are there any deviation in the soil samples properties at the begging of the study.
The duration of the experiment is 90 days, which could be too short and unusual that the duration of the experiment is limited in the physiological or technological maturity without going into the phases of plant development and growth dynamics, because it was a biological experiment. The authors should clearly explain the origin of the transplants and substrate use in this production.
From the picture of the field in the Figure 1 no visible plots/treatments can be identified. Please add what is the preceding crop type or plot history for this study and reflection on the experimental set up and soil properties.
What is difference between poultry waste and poultry litter it should be explained more precise
The research is based exclusively on soil properties and has no clear connection to crops or their influence on soil properties or changes in the crop development.
The conclusion should be clearer to indicate the type and dose of fertilizer that can be recommended for the application under specific soil and climate conditions. Also suggest that a

clear connection should be established with the crop that was used because it conditions the type and amount of organic fertilizer.
Finally, my recommendation is to make a significant revision of the text so that it can be accepted.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: agronomy and soil science

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 05 March 2026

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?

Jamal Abubaker
Sebha University Sebha, Sebha, Libya

Manuscript entitled "Mineral and organo-mineral fertilization alters soil Ca–Mg–K balance and base saturation during early coffee establishment”

This study examined the effects of different fertilizer types and poultry-based organic fertilizer rates on soil Ca, Mg, and K balance during early establishment of Arabica coffee in a clayey Red

Latosol in Brazil. A 3 × 4 factorial randomized block design tested mineral and organo-mineral fertilizers combined with four organic fertilizer rates. Soil analyses included exchangeable cations, cation ratios, base saturation, and potential acidity 90 days after transplanting. The study aimed to assess how fertilization strategies influence soil nutrient balance and potential risks of cation imbalances during early coffee growth.

The topic of the study is interesting; however, it contains miner issues that should be addressed. I have included my comments on each section and I hope they can help to improve it.

Abstract
- What do these numbers mean? "(MIN, 11-52-00), (OMF-CF, 06-30-00), (OMF-TF, 06-30-00)"
- "interactions for nine of ten indicators", unclear. What are these indicators?
- "(2, 4, 6 and 8 t ha?1)," revise it should be "ha-1"
- "Factorial analysis of variance", it is better to replace it with "Two-way ANOVA"

Keywords
- The keywords should be arranged in alphabetical order
- Additional keywords may be included to improve relevance and indexing, such as "Ca–Mg–K balance," "organo-mineral fertiliser," and "coffee establishment"

Introduction:

- "Establishing arabica coffee (*Coffea arabica* L.) requires soils with controlled acidity and adequate supplies of exchangeable base cations, because soil acidity simultaneously reduces Ca, Mg, and K availability and increases aluminium (Al) in phytotoxic forms (Quispe *et al.*, 2025)." why coffee seedlings are particularly sensitive to Ca–Mg–K imbalance?

- "Experimental evidence from greenhouse tomato seedlings demonstrates that balancing Ca, Mg, and K proportions relative to cation exchange capacity can reduce ionic competition and improve seedling growth", using tomato evidence in a coffee paper slightly inaccurate!! either briefly justify why tomato findings are used or add supporting evidence from coffee system

Materials and methods:

General comment: To avoid excessive condensation and improve e readability, the materials and methods section should be divided into clearly defined subsections. This will enhance the logical flow of information and make the experimental setup and design easier to follow, for example, the section could be organised into subsections such as: study site and soil characteristics; fertilisers and their composition; experimental design and setup; soil sampling and laboratory analyses; and statistical analysis.

- "Coffee seedlings were transplanted 40 days after fertiliser application (Day 40).
Clarification needed!!

why fertilization preceded transplanting by 40 days? was fertilizer incorporated?

Results:

- Soil samples collected 90 days after transplanting (0–20 cm) were analysed for exchangeable Ca, Mg and K and potential acidity (H+Al), and the derived cation ratios and cation exchange capacity (CEC)-based proportions were calculated.

This belongs in Materials and Methods, not results, results should focus on findings, not what was analysed

Discussion

- at the end of page 10: " Under these warm and wet conditions, microbial activity and organic-matter mineralization .....",
this is mechanistic speculation.

You did not measure microbial activity or mineralisation rate, you did not measure soil temperature or moisture directly or measure C dynamics!

- Page 11, "…. composition, processing and mineralisation kinetics (Soares et al., 2024", check the reference here if it should be "de Soares"

- community composition alongside changes in chemical attributes (Sant'Anna et al., 2024). check the reference here if it should be "Sant'anna"

- Page 7, interval was adopted to capture early fertiliser-induced soil chemical changes during coffee establishment (Afrizal et al., 2023). Check the publication year of the reference

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Not used in the paper

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Is the work clearly and accurately presented and does it cite the current literature?

Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
No source data required

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: My area of interest is to work with recycling of organic wastes as soil fertilizer and evaluate their effect on crop production, soil microorganisms, and greenhouse emission, mainly N2O from the soil.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.