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Deep soil tillage and mineral and organic fertilization for *Coffea canephora* cultivation

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ABSTRACT: In the state of Espírito Santo, Brazil, the production of conilon coffee plays a pivotal role in the economy, accounting for 75 % of national production. However, the growth of coffee roots is impeded by physical limitations in subsurface soil, primarily due to natural compaction, which restricts access to nutrients and water. To address these challenges, the implementation of deep soil tillage, along with mineral and organic fertilizers have been proposed as potential solution. These practices aim to alleviate or eliminate the constraints on root growth in deeper soil layers. The present study to assessed the effects of deep soil tillage and mineral and organic fertilization on coffee productivity and quality. The experiment was conducted in São Gabriel da Palha, Espírito Santo state, Brazil, following a simple arrangement of five treatments, employing a randomized block design with four replications. The treatments were as follows: t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, chicken manure, and biochar; t_3 = deep soil tillage at 150 cm depth and mineral fertilization; t_4 = deep soil tillage at 150 cm depth, mineral fertilizer, and chicken manure; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, chicken manure, and biochar. The outcomes of this study revealed that deep soil tillage, in conjunction with mineral and organic fertilization, significantly improved the chemical properties throughout the soil profile. This combination of practices increased accumulated productivity of up to 30 % following five consecutive coffee harvests. These findings underscore the importance of reducing or eliminating chemical constraints in cohesive soils as a pivotal practice for enhancing coffee yields.
Keywords: conilon coffee, cohesive soils, organic residues, soil porosity

Introduction

Conilon coffee (*Coffea canephora* (Pierre) ex Froehner) is a pivotal crop in Espírito Santo state, Brazil, accounting for 75 % of the country's production (INCAPER, 2020). Coffee stands as one of the most consumed beverages in the world, with millions of individuals consuming it on a daily basis. The coffee plant, indigenous to tropical regions, is renowned for its distinctive flavor and aroma; however, coffee production faces significant challenges, including soil constraints.

The cultivation of conilon coffee is often hindered by the presence of cohesive soils that restrict root development, limiting the plant's access to nutrients and water (Mullins et al., 1990). In response, the investigation of deep soil tillage and appropriate fertilization techniques as potential solutions has been undertaken. Soil constraints are physical, chemical, or biological factors impeding plant growth and productivity. These factors can prove particularly challenging for coffee production, given that the coffee plant is a perennial crop with a deep root system that requires a steady supply of nutrients and water (Tan et al., 2015). The nature of these constraints can vary depending on the geographical location and climatic conditions of the coffee plantation. However, some common examples include soil acidity, low fertility, high salinity, and poor pore distribution (Fageria and Baligar, 2008).

Therefore, it is imperative to implement effective soil management practices in order to overcome soil constraints in coffee production. Such practices may include the analysis of soil samples to ascertain nutrient deficiencies, the incorporation of organic matter to enhance soil structure and fertility, the utilization of cover crops to improve soil health, and the application of fertilizers and soil amendments to redress imbalances in nutrients (Chemura, 2014). In addition to these practices, conservation methods and irrigation management are integral to ensuring an adequate water supply for coffee plants (Covre et al., 2016). Consequently, effective soil management is paramount for overcoming soil-related limitations, optimizing coffee yields and quality (Melo et al., 2022).

Research concerning the intricacies of deep soil preparation, concomitant with mineral and organic fertilization, is still incipient in conilon coffee cultivation. The objective of this study was to ascertain the influence of deep soil tillage and the application of mineral and organic fertilizers on the productivity of conilon coffee. By delving into the intricate interplay between these techniques and the challenges posed by soil constraints, this research aimed to contribute valuable insights for enhancing conilon coffee cultivation. Therefore, a comprehensive examination of the methods employed in deep soil tillage and fertilization is undertaken, to formulate practical recommendations that can enhance yields, improve quality, and lay the foundation for sustainable and robust conilon coffee production.

Materials and Methods

Experimental setup

The experimental site is situated in the municipality of São Gabriel da Palha, Espírito Santo state, Brazil (19°01′00″ S, 40°32′11″ W, altitude 118 m). The soil at the site is classified as a (densic) Xanthic hapludox, as defined by the Soil Survey Staff (2022). The site's topography is characterized by slight undulations, with an approximate slope of 8 %. The Köppen climate classification indicates that the region has tropical Aw type (Köppen, 1936), with a dry winter season from April to September and an average, precipitation rainfall of less than 60 mm, and a rainy summer season from October to March with an average rainfall of 150 mm.

Before initiating the experimental protocol, soil samples were collected from the following layers: 0-10, 10-20, 20-40, 40-60, 60-100, and 100-150 cm. These samples were then subjected to chemical and physical analyses to determine their characteristics. The results of these analyses are outlined in Table 1.

Experimental arrangement

The study was designed incorporating a simple experimental arrangement comprising five distinct treatments that integrated soil tillage and fertilization methodologies:

Treatment 1 (t_1): Soil tillage at 60 cm depth and standard fertilization;

Treatment 2 (t_2): Soil tillage at 60 cm depth, mineral fertilizer, chicken manure, and biochar;

Treatment 3 (t_3): Deep soil tillage at 150 cm depth and mineral fertilization;

Treatment 4 (t_4): Deep soil tillage at 150 cm depth, mineral fertilizer, and chicken manure;

Treatment 5 (t_5): Deep soil tillage at 150 cm depth, mineral fertilizer, chicken manure, and biochar.

The experimental design employed a randomized complete block configuration, with four replicates and a single clone allocated to each block. The selection of clones 02, LB1, P1, and 13 was predicated on their documented productivity and favor among regional producers. The experimental unit comprised a single row with seven plants and a spacing configuration of 1 × 1 m between plants. The central three plants constituted the designated useful plot.

Soil tillage and fertilization

Conventional soil tillage for coffee planting was performed by subsoiling at a depth of 60 cm. For deep soil tillage, a backhoe was used to dig trenches 80 cm wide and 150 cm deep (Figure 1).

The biochar utilized in this study was produced from eucalyptus biomass, and following a process of

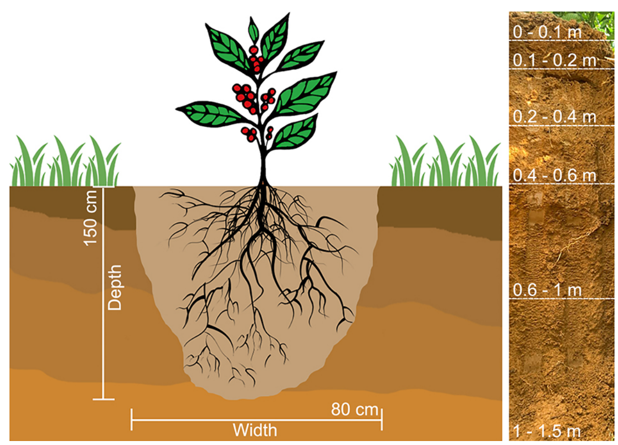

Figure 1 – Illustration of deep tillage and layers sampled for coffee planting.

Table 1 – Chemical and physical soil characteristics of (densic) Xanthic hapludox prior to the coffee planting.

Depth	pH	P	K	S	Ca^{2+}	Mg^{2+}	Al^{3+}	HAl	CEC	*c*P-rem	Mn	B	Cu	Zn	SOM	Sand	Silt	Clay	DSoil
cm	H_2O	-------- mg dm^{-3} --------			------------ $cmol_c$ dm^{-3} ------------					mg L^{-1}	------------ mg dm^{-3} ------------				g kg^{-1}	------------ % ------------			kg dm^{-3}
0.0-10	5.58	13.50	105.00	3.10	2.63	0.92	0.00	3.60	7.42	40.10	31.80	0.85	0.37	2.07	27.10	49.10	1.70	49.20	1.42
10-20	4.89	10.40	31.00	0.10	1.18	0.30	0.10	3.20	4.76	39.90	9.20	0.77	0.31	1.16	14.90	41.60	6.00	52.40	1.49
20-40	4.48	3.50	19.00	2.80	1.13	0.28	0.39	2.90	4.36	33.50	2.30	0.50	0.22	0.27	10.90	36.40	1.30	62.30	1.55
40-60	4.27	1.00	4.00	6.60	0.94	0.19	0.69	3.40	4.54	31.40	1.30	0.45	0.23	0.35	10.90	32.00	2.00	66.00	1.41
60-100	4.27	0.80	4.00	13.80	0.86	0.17	0.69	2.60	3.64	28.10	1.40	0.45	0.32	0.27	8.10	31.60	3.00	65.40	1.49
100-150	4.13	2.20	2.00	34.20	0.53	0.19	0.69	2.60	3.33	26.80	2.50	0.45	0.32	0.39	5.40	29.90	2.20	68.00	1.33

Soil samples collected in Dec 2017. pH in water (L:S 2.5 L kg^{-1}); exchangeable Ca^{2+}, Mg^{2+}, Al^{3+} in a 1 mol L^{-1} KCl soil extract; available P, K, Mn, Cu, and Zn extracted by Mehlich 1; S extracted by monocalcium phosphate 500 mg L^{-1} P in 2 mol L^{-1} acetic acid; B extracted by hot water; H + Al extracted by Ca acetate 0.5 mol L^{-1}, pH 7.0. Particle size analysis with the pipette. CEC = cation exchange capacity; *c*P-rem = equilibrium phosphorous; SOM = soil organic matter by Walkley-Black method; Dsoil = volumetric flask method.

trituration, it exhibited a density of 0.55 kg dm^{-3}. The granulometry of the biochar is delineated as follows: > 4 mm: 11.9 %, 2-4 mm: 15 %, 1-2 mm: 12.7 %, 0.25-1 mm: 27.4 %, and < 0.25 mm: 33.1 %. The chicken manure sample initially had a moisture content of 59 %, and following the drying process, its density reached 0.5 kg dm^{-3}. The nutrient contents of both chicken manure and biochar are outlined in Table 2.

Specific amounts of limestone, gypsum, chicken manure, biochar, and fertilizers were utilized during the planting phase, as delineated in Table 3. These corrective measures, along with mineral and organic fertilizers, were uniformly mixed into the soil and reintroduced into the trench, ensuring uniform distribution and preventing the formation of depressions that could potentially result in water accumulation and subsequent drowning.

Planting and irrigation

In Dec 2017, the seedlings were planted with a spacing of 3 × 1 m. However, the specific arrangements differed depending on the tillage treatment. In the case of deep tillage (t_3, t_4, and t_5), each plant was allocated a volume of prepared soil measuring 1200 dm^{-3} (80 × 100 × 150: width, length, and depth). Conversely, for the conventional tillage treatments (t_1 and t_2), the soil volume per plant was approximately 150 dm^{-3} (30 × 100 × 50: width, length, and depth).

Table 2 – Nutrient content of chicken manure and biochar.

	C	N	P	K	Ca	Mg	S	B	Mn	Fe	Al
	g kg^{-1}										
Chicken manure	250	21	4.7	16.9	7.3	4.4	2.9	0.024	0.584	1.43	-
Biochar	69	0.7	0.21	0.45	2.4	0.28	0.11	0.007	0.055	0.32	0.62

The irrigation system employed in this study was a micro spray, which delivered water at a rate of 14 L h^{-1} per plant. During the implementation phase, all treatments received an equal amount of water. However, in the production phase (two years after planting), irrigation frequency was reduced by 50 % in the deep soil tillage treatments (t_3, t_4, and t_5).

Assessments

Soil samples were collected at two-time points: 9 and 26 months after planting. These samples were collected across various depths: 0-20, 20-40, 40-80, and 80-150 cm. Leaf samples collected in Feb 2020 were subjected to plant tissue analysis. Nutritional diagnosis was performed using the Diagnosis and Recommendation Integrated System (DRIS) and the Balanced Indexes of Kenworthy (BIK) methods, as outlined in Table 4. The NUTRICAFÉ-UFV system (Leite et al., 2009) was employed, utilizing the criteria established for conilon coffee.

Root development was assessed by collecting soil samples at four distinct depths: 0-20, 20-40, 40-60, and 60-100 cm. These samples were collected using a soil auger, obtaining 200 cm^3 of soil at the first three depths and 400 cm^3 at the last. After collection, the soil was subjected to air-drying. All roots were then collected and stored in a 20 % alcohol solution. WinRHIZO software (2009) was then utilized to meticulously evaluate parameters such as surface area, root tips, and forks.

From 2019 to 2023, five coffee harvests were conducted, and ripe coffee yield was assessed on the three plants within the designated plot area. The estimated yield of processed coffee, measured in bags per hectare (bags ha^{-1}), was determined by dividing

Table 3 – Quantities of limestone, gypsum, chicken manure, biochar, and fertilizers used at coffee planting.

Treatment	Tillage	Limestone	Gypsum	Chicken manure	Biochar	SSP	P-Reactive	MAP	Urea	KCl	Ulexita	ZnO
		kg m^{-1}			L m^{-1}	g m^{-1}						
t_1	Conventional	0.3	0.15	0.5	-	150	200	-	-	-	-	-
t_2	Conventional	0.8	0.3	2.5	12	50	321	212	178	133	4.43	1.6
t_3	Deep + Mineral	2.4	0.9	-	-	50	962	635	533	400	13.3	4.8
t_4	Deep + Mineral + Chicken Manure	2.4	0.9	7.5		50	962	635	533	400	13.3	4.8
t_5	Deep + Mineral + Chicken Manure + Biochar	2.4	0.9	7.5	36	50	962	635	533	400	13.3	4.8

t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, chicken manure, and biochar; t_3 = deep soil tillage at 150 cm depth and mineral fertilization; t_4 = deep soil tillage at 150 cm depth, mineral fertilizer, and chicken manure; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, chicken manure, and biochar. SSP = simple superphosphate; MAP = monoammonium phosphate; KCl = potassium chloride.

Table 4 – Nutritional reference values Cooabriel VI for nutritional analysis using the Diagnosis and Recommendation Integrated System and Balanced Indexes of Kenworthy methods.

Parameters	P	K	Ca	Mg	S	Cu	Fe	Zn	Mn	B
	g kg^{-1}					mg kg^{-1}				
Mean	1.23	15.19	14.40	2.65	1.61	9.10	104.10	8.8	111. 80	66.40
Standard Deviation	0.16	2.20	2.97	0.83	0.42	4.75	38.49	3.8	88.54	15.53
CV	12.8	14.50	20.60	31.30	25.80	52.30	37	43.3	79.20	23.40

CV = coefficient of variation.

the field's yield of 310 L of ripe coffee by the yield equivalent of each bag of processed coffee (60 kg). The coffee yield was computed over six years, with a single yield annually following the initial year.

Coffee quality

The coffee quality was evaluated by a certified taster accredited by the Brazil Specialty Coffee Association (BSCA, 2024), with a Q Grader certification.

Statistical analysis

Significant differences were determined using analysis of variance (ANOVA) at $p < 0.1$, $p < 0.05$, and $p < 0.01$, and the degrees of freedom were parsed using orthogonal contrasts. This involved the computation of four orthogonal contrasts (C_1, C_2, C_3, C_4) and two additional contrasts (C_{A1}, C_{A2}). The 5 % Tukey's range test was also employed to compare the means corresponding to cumulative yield.

Results

Chemical characteristics of the soil

Prior to planting, the soil exhibited pH values below 5.5 across the entire profile, with a minimum value of 4.13 (Figure 2). However, the implementation of deep tillage techniques, particularly in t_5, increased of pH levels above 5.5 throughout the soil profile. Conversely, conventional tillage methods (t_1 and t_2) did not result in any significant changes in the deeper soil layers, demonstrating the inability to correct the acidity limitations in those layers due to the lack of lime incorporation beyond 50 cm, which could be attributed to the low mobility of limestone, especially in soils that exhibit cohesive characteristics in subsurface layers (Cavalcanti et al., 2019).

In general, in soils with a pH below 5.5, limitations to growth may occur due to high concentrations of potentially toxic elements, such as Al^{3+}. Thus, in the treatments that received higher doses of limestone (t_3, t_4, and t_5) and where deep tillage was conducted, the content of Al^{3+} along the soil profile was lower (Figure 2).

The results of the soil chemical analysis conducted nine months after planting (Table 5) indicate a more consistent distribution of phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) throughout the soil profile when using trenching as opposed to conventional tillage methods, such as subsoiling.

The treatments involving deep soil tillage exhibited higher Ca and Mg levels along the soil profile. This finding indicates the positive impact of lime incorporation as a nutrient source. However, similar to the pH levels, the Ca and Mg content fell below the desired range. This suggests a potential underestimation of the liming requirements in these specific conditions (Figure 3).

The deep soil tillage treatments exhibited elevated levels of P and K in the subsurface layers in comparison to conventional tillage. As depth increased, the levels of these nutrients also increased, surpassing critical thresholds in the soil. The critical thresholds were 25 mg dm^{-3} for P and 100 mg dm^{-3} for K (Figure 4). Conversely, the conventional soil tillage treatments exhibited suboptimal levels of these nutrients, which hindered the promotion of optimal root growth.

The deep soil tillage treatments exhibited heightened levels of zinc (Zn) and boron (B) across the soil profile compared to conventional soil tillage. These levels surpassed the critical thresholds of 2 mg dm^{-3} for Zn and 0.6 mg dm^{-3} for B (Figure 5). Conversely, treatments involving conventional soil tillage exhibited inadequate levels of Zn, falling below the critical threshold.

The incorporation of organic sources, specifically involving deep soil tillage, chicken manure, and biochar (t_4 and t_5), resulted in a notable increase in soil organic matter (SOM) levels along the soil profile (Figure 6), showing the most significant improvements.

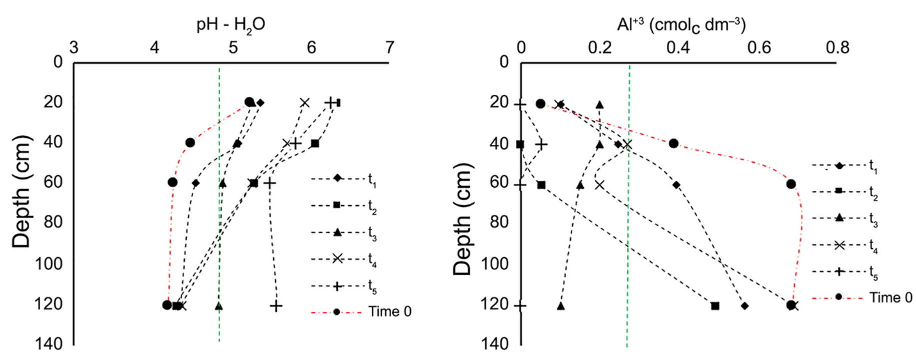

Figure 2 – pH in H_2O and exchangeable Al along the profile, at time 0 and 9 months after planting; the green line represents the critical level. t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, chicken manure, and biochar; t_3 = deep soil tillage at 150 cm depth and mineral fertilization; t_4 = deep soil tillage at 150 cm depth, mineral fertilizer, and chicken manure; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, chicken manure, and biochar.

Table 5 – Chemical characteristics of soil (densic) Xanthic hapludox nine months after the coffee planting.

Treatment	Depth	pH	P	K	Ca^{2+}	Mg^{2+}	Al^{3+}	t	T	*c*P-rem	Mn	S	Zn	V
	m	H_2O	------- mg dm^{-3} -------		------------------------ $cmol_c$ dm^{-3} ------------------------					mg L^{-1}	------------- mg dm^{-3} -------------			%
t_1	0.0-0.2	5.38	76.00	54.50	1.74	0.40	0.14	2.43	4.23	33.95	5.50	74.20	1.44	53.55
	0.2-0.4	5.10	5.00	34.00	0.88	0.35	0.48	1.80	4.32	34.60	6.10	66.30	0.61	30.60
	0.4-0.8	4.55	3.10	27.00	0.88	0.40	0.67	2.02	4.35	33.20	6.00	60.50	0.54	31.00
	0.8-1.5	4.36	3.60	20.00	0.36	0.21	1.06	1.68	4.12	29.20	7.70	45.20	2.42	15.00
t_2	0.0-0.2	6.32	168.00	127.50	2.15	0.53	0.09	3.11	5.72	41.25	7.20	31.90	0.97	52.40
	0.2-0.4	6.06	22.10	117.00	1.27	0.34	0.39	2.30	5.21	36.80	7.30	51.50	1.00	36.70
	0.4-0.8	5.38	7.40	113.00	0.75	0.32	0.67	2.03	5.06	34.50	5.50	55.50	0.72	26.90
	0.8-1.5	4.30	14.90	93.00	0.47	0.21	1.06	1.98	4.42	28.70	4.00	99.20	0.66	20.80
t_3	0.0-0.2	5.27	13.80	53.00	0.70	0.25	0.43	1.53	3.94	32.10	3.60	33.70	1.09	27.80
	0.2-0.4	5.10	21.70	77.00	1.06	0.32	0.29	1.87	4.28	34.00	4.20	39.30	1.75	36.90
	0.4-0.8	4.90	34.40	79.00	1.29	0.37	0.19	2.05	4.36	36.20	2.80	44.70	2.68	42.70
	0.8-1.5	4.83	42.00	63.00	1.32	0.39	0.19	2.06	4.77	34.80	3.10	51.00	1.43	39.20
t_4	0.0-0.2	5.92	175.50	228.00	2.69	0.89	0.00	4.17	6.07	41.60	11.75	10.55	6.60	68.65
	0.2-0.4	5.71	100.00	266.00	1.52	0.48	0.00	2.68	5.38	41.50	4.80	27.20	5.17	49.80
	0.4-0.8	5.30	38.00	189.00	1.80	0.44	0.00	2.72	5.12	40.50	7.80	38.00	2.40	53.10
	0.8-1.5	4.37	142.00	224.00	2.99	0.85	0.00	4.41	6.51	37.50	7.60	37.50	4.75	67.70
t_5	0.0-0.2	6.26	180.00	227.00	2.37	0.91	0.00	3.87	5.72	42.55	10.50	8.30	7.09	66.95
	0.2-0.4	5.82	41.00	244.00	1.20	0.38	0.10	2.31	5.11	40.50	6.40	29.40	2.06	43.20
	0.4-0.8	5.50	118.00	162.00	1.86	0.50	0.00	2.78	5.48	41.70	6.90	42.50	3.27	50.70
	0.8-1.5	5.60	51.00	167.00	2.34	0.64	0.00	3.41	5.81	35.70	8.10	52.80	3.56	58.70

pH in water (L:S 2.5 L kg^{-1}); exchangeable Ca^{2+}, Mg^{2+}, Al^{3+} in a 1 mol L^{-1} KCl soil extract; available P, K, Mn, and Zn extracted by Mehlich 1; available S extracted by monocalcium phosphate 500 mg L^{-1} P in 2 mol L^{-1} acetic acid; t = effective cation exchange capacity; T = cation exchange capacity at pH 7.0; *c*P-rem = equilibrium phosphorous; V = base saturation. Particle size analysis with the pipette method. t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, chicken manure, and biochar; t_3 = deep soil tillage at 150 cm depth and mineral fertilization; t_4 = deep soil tillage at 150 cm depth, mineral fertilizer, and chicken manure; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, chicken manure, and biochar.

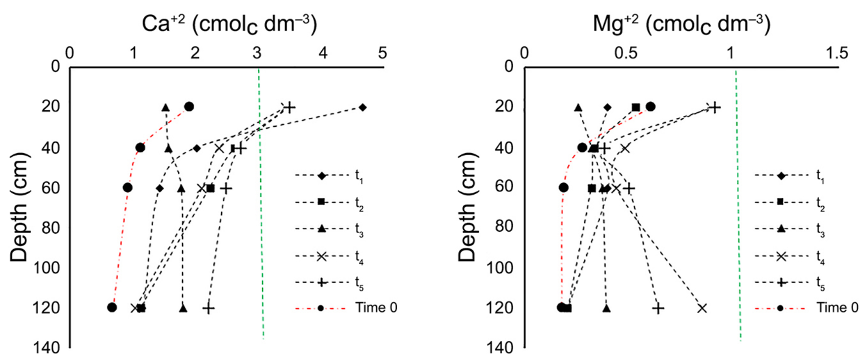

Figure 3 – Ca and Mg contents in the different soil layers at time zero and after planting; green line represents the critical level. t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, chicken manure, and biochar; t_3 = deep soil tillage at 150 cm depth and mineral fertilization; t_4 = deep soil tillage at 150 cm depth, mineral fertilizer, and chicken manure; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, chicken manure, and biochar.

Nutritional status of coffee plants

The application of the DRIS method for nutritional diagnosis and the assessment of the BIK (Table 6) collectively indicate that, overall, minimal nutrient constraints influenced coffee tree growth and production. An exception arose in t_2, in which an imbalanced nutritional status was observed, specifically in terms of Zn and B levels. In the DRIS method, values below –1.5 were categorized as deficient, while values above 1.5 were considered excessive. The BIK delineates sufficiency levels with an initial threshold of 83 % of the optimal level and an upper limit of 150 % of the optimal level (Fonseca et al., 2018).

Root growth

The treatments involving deep tillage (t_4 and t_5) exhibited superior root development compared to conventional tillage (t_1 and t_2), except for t_3, which lacked an organic source. The findings indicate a more significant number of root tips in the treatments

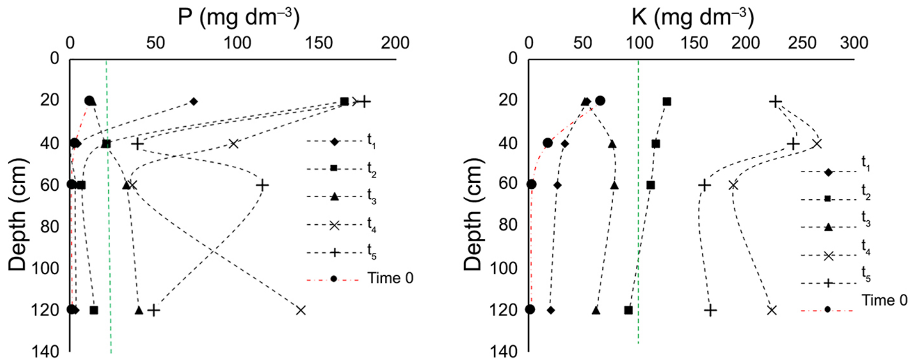

Figure 4 – P and K contents in the different soil layers at time zero and after planting; green line represents the critical level. t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, chicken manure, and biochar; t_3 = deep soil tillage at 150 cm depth and mineral fertilization; t_4 = deep soil tillage at 150 cm depth, mineral fertilizer, and chicken manure; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, chicken manure, and biochar.

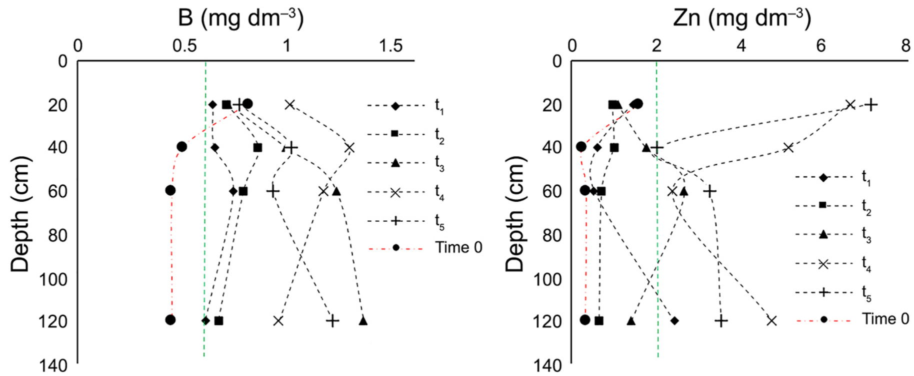

Figure 5 – B and Zn contents in the different soil layers at time zero and after planting; green line represents the critical level. t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, chicken manure, and biochar; t_3 = deep soil tillage at 150 cm depth and mineral fertilization; t_4 = deep soil tillage at 150 cm depth, mineral fertilizer, and chicken manure; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, chicken manure, and biochar.

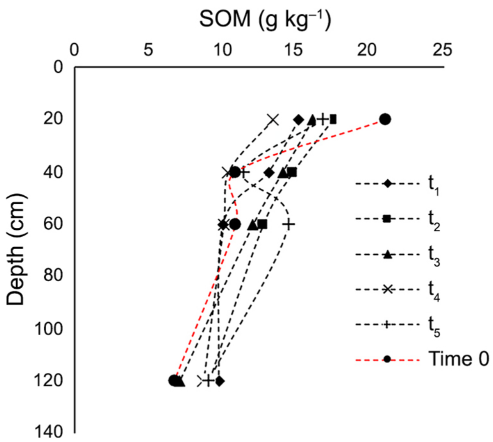

Figure 6 – Soil organic matter (SOM) content in different soil layers at time zero and after planting. t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, chicken manure, and biochar; t_3 = deep soil tillage at 150 cm depth and mineral fertilization; t_4 = deep soil tillage at 150 cm depth, mineral fertilizer, and chicken manure; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, chicken manure, and biochar.

incorporating deep tillage and organic sources (t_4 and t_5) in contrast to those with conventional tillage (Figure 7). Furthermore, the results demonstrated a more significant number of forks in the root system in the deep tillage treatments, indicating a greater surface area (Figure 7).

Coffee yield

During the vegetative cycle of coffee trees, a notable distinction in vegetative growth was observed among the treatments involving deep tillage (t_3, t_4, and t_5) and conventional tillage (t_1 and t_2). The plants subjected to deep tillage exhibited significantly superior vegetative growth compared to conventional tillage treatments.

The enhanced vegetative growth in the deep tillage treatments resulted in elevated accumulated yields across the five harvests, with t_3 yielding 600.97 (ab) bags ha^{-1}, t_4 yielding 656.07 (a) bags ha^{-1}, and t_5 yielding 643.56 (a) bags ha^{-1}. In contrast, the conventional tillage treatments, in conjunction with the application of high nutrient and organic matter sources

Table 6 – Nutritional diagnosis with Diagnosis and Recommendation Integrated System (DRIS) and Balanced Indexes of Kenworthy (BIK) methods of the coffee plants.

Treatment	Method	P	K	Ca	Mg	S	Cu	Fe	Zn	Mn	B
t_1	DRIS	0.18	−0.16	0.43	0.46	1.36	−0.52	−0.72	−1.15	0.4	−0.29
t_2		0.36	1.33	0.72	0.72	1.36	−1.15	−0.5	−1.57	0.41	−1.69
t_3		0.19	0.84	0.23	0.52	1.04	−0.04	−1.13	−1.13	0.32	−0.82
t_4		−0.04	1.1	0.51	0.58	0.94	−0.16	−1.23	−1.06	0.31	−0.95
t_5		0.03	1.11	0.89	0.74	1.11	−0.22	−1.49	−1.26	0.34	−1.25
t_1	BIK	109	98	111	113	149	83	80	74	102	92
t_2		113	140	113	118	142	73	82	69	100	66
t_3		114	132	107	117	139	96	73	75	102	82
t_4		113	148	120	124	141	95	74	78	103	83
t_5		112	144	127	127	144	92	69	75	102	76

Excessive | Above normal | Normal | Below normal | Deficient

t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, chicken manure, and biochar; t_3 = deep soil tillage at 150 cm depth and mineral fertilization; t_4 = deep soil tillage at 150 cm depth, mineral fertilizer, and chicken manure; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, chicken manure, and biochar.

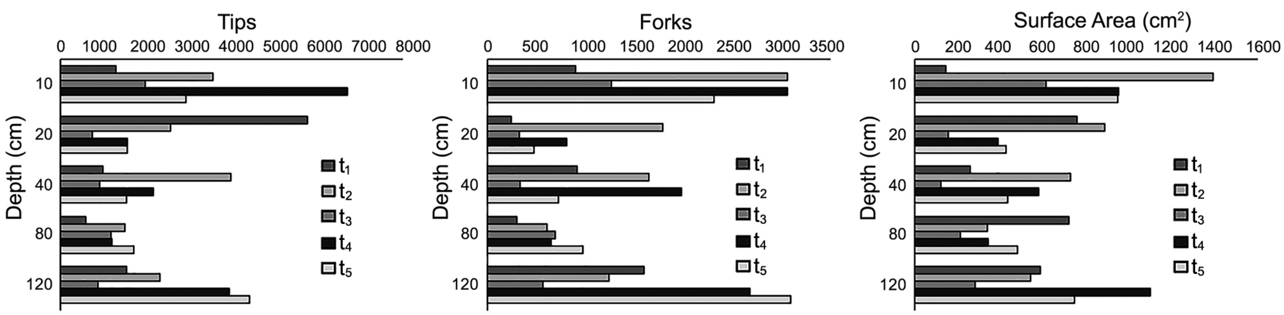

Figure 7 – Root development along the soil profile. t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, chicken manure, and biochar; t_3 = deep soil tillage at 150 cm depth and mineral fertilization; t_4 = deep soil tillage at 150 cm depth, mineral fertilizer, and chicken manure; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, chicken manure, and biochar.

on the soil surface (t_2) and the standard producer approach (t_1), yielded 572.27 (ab) and 504.09 (b) bags ha^{-1}, respectively (Figure 8).

In the present study, an evaluation was conducted on a series of conilon coffee clones. The analysis revealed that clone 12 exhibited the lowest quality score when compared to clones lb1, 13, and P1. Furthermore, the accumulated yield of clones 12 and 13 was lower than that of clones lb1 and P1. It is noteworthy that clone P1 exhibited a significantly higher yield than the other clones (Figure 9).

Statistical analysis

Statistical disparities in the orthogonal contrasts were ascertained when examining the temporal contrasts (Table 7). This entailed an assessment of the cumulative crop yields over the years 2019-2021, 2019-2022, and 2019-2023. In the context of Contrast 1 (C_1), which investigated the influence of soil preparation (p50 vs p150), a statistically significant difference, $p < 0.01$, emerged across all three time periods. Notably, the deep soil preparation treatments exhibited substantially superior

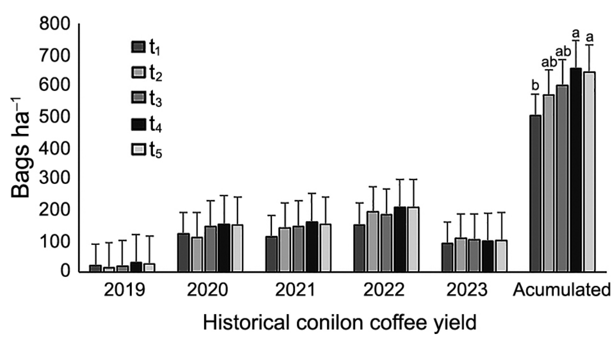

Figure 8 – Historical conilon coffee yield and cumulative yield as a function of soil tillage and fertilization. Means with the same letter do not differ by the Tukey's test ($p < 0.05$). t_1 = soil tillage at 60 cm depth and standard fertilization, 504.09 (b) bags ha^{-1}; t_2 = soil tillage at 60 cm depth, mineral fertilizer, chicken manure, and biochar, 572.27 (ab) bags ha^{-1}; t_3 = deep soil tillage at 150 cm depth and mineral fertilization, 600.97 (ab) bags ha^{-1}; t_4 = deep soil tillage at 150 cm depth, mineral fertilizer, and chicken manure, 656.07 (a) bags ha^{-1}; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, chicken manure, and biochar, 643.56 (a) bags ha^{-1}.

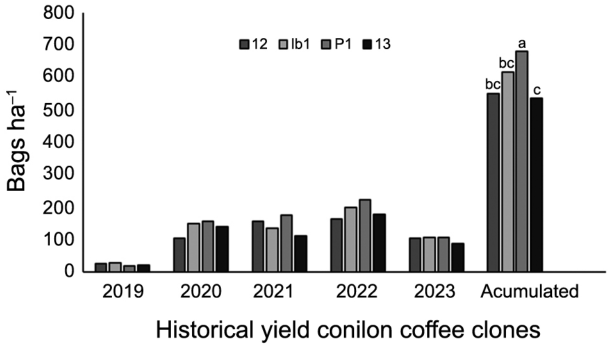

Figure 9 – Yield of historical conilon coffee clones 12, lb1, P1 and 13. Means with the same letter do not differ by the Tukey's test (p < 0.05).

Table 7 – Orthogonal contrast of the accumulated yield.

Orthogonal contrasts		Mean contrasts Ckm = Σ_i c_ik T_i / r (Σ_i |c_ik|/2)		
Accumulated yield		2019-2021	2019-2022	2019-2023
C_1	$t_1 + t_2$ vs $t_3 + t_4 + t_5$	66.19**	93.50**	95.36**
C_2	t_1 vs t_2	9.86ns	51.52ns	68.18ns
C_3	t_3 vs $t_4 + t_5$	27.32***	51.62***	48.85ns
C_4	t_4 vs t_5	−14.83ns	−14.37ns	−12.51ns
CA_1	t_2 vs t_5	62.96**	77.77*	71.29***
CA_2	t_3 vs t_4	34.73***	58.81***	55.10ns

*Significant. **Highly significant. ***Significant at 10 %. ns = not significant; Ckm = mean contrasts; C_1 = orthogonal contrast 1; C_2 = orthogonal contrast 2; C_3 = orthogonal contrast 3; C_4 = orthogonal contrast 4; CA_1 = additional orthogonal contrast 1; CA_2 = additional orthogonal contrast 2. t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, chicken manure, and biochar; t_3 = deep soil tillage at 150 cm depth and mineral fertilization; t_4 = deep soil tillage at 150 cm depth, mineral fertilizer, and chicken manure; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, chicken manure, and biochar.

yields of 66.19, 93.50, and 95.36 bags ha^{-1}during 2019-2021, 2019-2022, and 2019-2023, respectively, compared to their conventional soil preparation counterparts.

In Contrast 2 (C_2), despite no statistical differences, p > 0.05, comprehensive fertilization in conventional tillage resulted in a notable yield increase of 68.18 bags ha^{-1} from 2019 to 2023 compared to standard fertilization. Contrast 3 (C_3) showed statistical differences, p < 0.10, for treatments combining deep soil preparation with mineral and organic fertilization, yielding 27.32 and 51.62 bags ha^{-1} more during 2019-2021 and 2019-2022, respectively, than deep soil tillage with mineral fertilization.

In the conilon course of the investigation, it was determined that among the coffee clones under consideration, clone 12 exhibited the lowest quality score compared to clones lb1, 13, and P1 (Table 8). Furthermore, apart from quality considerations, the combined yield of clone 12 and 13, fell below that of clones lb1 and P1. Notably, clone P1 displayed a significantly higher yield than the other evaluated clones (Figure 9).

Table 8 – Averages of final score for beverage quality for four clones of conilon coffee.

Clones	Quality	Score
12	76.4	Very good
lb1	80.7	Fine
P1	81.7	Fine
13	80.4	Fine

Discussion

The productivity of coffee plants is influenced by various factors, including the of soil's physical, chemical, and biological characteristics, genetic materials (Partelli et al., 2013), and favorable climatic conditions (Pratama and Rachman, 2024). When establishing coffee cultivation, it becomes crucial to select clones well adapted to the soil and climate conditions of the region. This ensures optimal growth and development of the coffee plant, leading to improved yields throughout its vegetative cycle. This, in turn, improves crop profitability, as evidenced in this study.

Soil analyses over time have demonstrated increased nutritional levels throughout the profile. This finding suggests that improving the subsoil's nutritional conditions plays a pivotal role in plant growth and development. These results underscore the necessity of considering nutrient distribution in the soil and management strategies that prioritize not only the soil surface layer but also the improvement of the nutritional status of the subsoil to optimize plant root exploration.

The enhancement of root growth can be attributed to numerous factors. Among these, the modification of soil structure through deep soil tillage practices has been demonstrated to reduce compaction, thereby establishing a conducive environment for root growth, resulting in an increased number of root tips and branching (Silva et al., 2021). Incorporating organic sources, such as chicken manure and biochar, has enhanced soil fertility and nutrient availability, providing essential root proliferation elements (Figure 7) (Zhang et al., 2020). These findings are consistent with the conclusions of previous studies that have also shown the positive impact of organic source incorporations on SOM content in agricultural soils (Holatko et al., 2022). The addition of organic sources, such as chicken manure and biochar, has been shown to enhance the accumulation of stable carbon compounds in the soil, thereby increasing SOM levels (Sánchez-Monedero et al., 2019). Conversely, the practice of deep tillage has been observed to promote the incorporation and mixing of organic materials, facilitating their interaction with the soil matrix, decomposition, and SOM stabilization (Song et al., 2016). Consequently, the enhancement of SOM levels throughout the soil profile is essential for soil fertility, nutrient cycling, water retention, and overall soil health (Diacono and Montemurro, 2010).

It is imperative to note that adequate levels of P and K are paramount for the optimal performance of the crop. These elements are required in larger quantities to support critical physiological processes, including photosynthesis, energy transfer and metabolism, protein synthesis, water regulation, root growth and development, and the transport of nutrients and sugars throughout the plant (Khan et al., 2023; Wang et al., 2013). Treatments involving deep soil tillage resulted in higher levels of P and K in the sub-surface layers compared to conventional tillage systems (Figure 4). This finding is consistent with studies reporting greater nutrient availability in deeper soil layers due to deep mobilization practices (Alves et al., 2022). The findings underscore the importance of maintaining critical thresholds throughout the soil profile, as observed in treatments with deep tillage, to ensure optimal plant development. This is because the critical level represents the minimum concentrations of nutrients necessary for soil to support optimal plant growth and productivity (Bragança et al., 2007). The capacity of deep soil tillage treatments to enhance nutrient distribution in the sub-surface layers can be attributed to soil tillage and mixing, which facilitates nutrient movement and accumulation (Cai et al., 2014). The recurrent disruption of the soil surface due to conventional tillage methods may result in nutrient imbalance, leading to diminished micronutrient concentrations in the upper soil layers. Therefore, ensuring adequate micronutrient levels throughout the soil profile is imperative for optimal plant nutrition and to avert deficiencies (Dubberstein et al., 2019). These findings underscore the potential benefits of deep soil tillage in enhancing micronutrient availability, exceeding the critical levels necessary for optimal coffee tree growth (Cai et al., 2014). Conversely, treatments involving conventional tillage exhibited inadequate micronutrient levels, falling below the critical threshold. This finding is consistent with studies reporting Zn deficiencies in the surface layers of soil under conventional practices (Pedrosa et al., 2013).

This study examined the challenges posed by persistently low initial soil pH values, frequently below 5 and reaching a minimum of 4.13, indicative of acidic soil conditions. Such acidity has been demonstrated to impede plant growth and nutrient absorption, and it has been linked to elevated concentrations of potentially toxic Al^{+3} (Zhou et al., 2015). In response to these findings, a set of techniques were employed to address the issue of acidity soil, with a focus on the deep soil tillage system. These techniques led to a notable increase in soil pH levels throughout the profile, with values surpassing the critical threshold of 5.5. This improvement was attributed to the incorporation of limestone during the soil preparation stage. Limestone has been identified as a method to neutralize soil acidity by releasing calcium ions (Ca^{2+}) and reducing aluminum ions (Al^{+3}) (Brady and Weil, 2008). These outcomes were consistent with the findings of research on the efficacy of limestone application incorporated into subsurface layers, which has been demonstrated to increase soil pH levels (Campos et al., 2022). The study also revealed high levels of Ca and Mg in treatments involving deep soil tillage compared to the conventional system, attributing this result to the incorporation of dolomitic limestone, recognized not only as a soil acidity corrector but also as a supplier of essential elements, such as Ca and Mg, improving soil fertility (Moreira et al., 2024). However, despite these observed enhancements, the levels of Ca and Mg remained below the optimal range. This phenomenon may be attributed to an underestimation of liming requirements, which are influenced by factors such as initial soil pH and the nutritional demands of the cultivating crop (Teixeira et al., 2020). These findings underscore the necessity of accurate soil analysis and the implementation of optimal liming practices to enhance crop growth and productivity (Fageria and Baligar, 2008).

However, the findings of this study suggest that deep tillage practices positively impacted the productivity of conilon coffee, with increases of up to 30 % compared to conventional tillage methods. It is noteworthy that in addition to higher productivity, these treatments under deep tillage received 50 % of the irrigation after the second year of planting compared to treatments under conventional tillage. These results are consistent with those reported by El-Nagar and EL-Gohary (2022), who found that crops prepared with deep soil exhibited greater efficiency in water consumption under irrigation systems. The observed increase in productivity can be attributed to various factors associated with deep tillage, including improved soil structure, increased nutrient availability, and enhanced root development (Silva et al., 2021). The findings of this study are consistent with research demonstrating the positive effects of deep tillage on crop yield (Azevedo et al., 2023). Similar results have been reported for various crops, highlighting the benefits of deep tillage for improving vegetative growth and increasing yield (Unger, 1979).

Quality is a pivotal aspect of coffee production, influenced by various factors such as bean size, shape, color, aroma, flavor, and score in coffee cupping. Research indicates that clones with higher yields tend to receive higher quality scores (Partelli et al., 2013). Selecting clones with desirable attributes is crucial to meet market preferences and ensure consumer satisfaction. The literature extensively documents the variation in quality and productivity among conilon coffee clones. Genetic factors, including specific characteristics and inherent variability among clones, contribute to observed differences in quality and productivity performance (Bragança et al., 2001).

Therefore, addressing the physical and chemical limitations of cohesive soils has been demonstrated to improve productivity and significantly reduced cost during the formation phase of conilon coffee (*C. canephora*) plants. By investing in deep soil mobilization and creating favorable conditions at planting time, farmers can maximize productivity and minimize expenses associated with plant establishment. This, in turn, can lead to a more efficient and profitable coffee production system.

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Authors' Contributions

Conceptualization: Calvache DFA, Mattiello EM, Castro GF, Assis IR. **Formal Analysis:** Calvache DFA, Mattiello EM, Castro GF, Cuichán CMV. **Methodology:** Calvache DFA, Mattiello EM, Assis IR. **Writing-original draft:** Calvache DFA, Mattiello EM, Castro GF, Cuichán CMV.

Conflict of interest

The authors declare that no conflicts of interest could have influenced the research, results, or interpretations presented.

Data availability statement

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

Declaration of use of AI Technologies

Artificial intelligence was utilized to enhance the readability and language of this work. However, AI technologies were not used to generate or analyze the results presented in this study. All results are based on original research and analysis conducted by the authors.

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