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Soil nutrient improvement with organic amendments: a basis for lemon orchard management

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ABSTRACT

Lemon trees require the nutrients they extract from the soil. This research aims to analyze the impact of organic matter application on enhancing soil nutrient availability and improving soil chemical properties using a pot-scale incubation experiment. This study used a completely randomized design with eight treatments and four replications. The pot treatment used 10 kg of air-dry soil per pot mixed with an organic matter dosage of 30 tons ha^{-1} and was observed at 2, 4, 8 weeks after applications. The treatment consisted of P1 (topsoil, control), P2 (subsoil, control), P3 (topsoil + compost), P4 (subsoil + compost), P5 (topsoil + cow manure), P6 (subsoil + cow manure), P7 (topsoil + goat manure), and P8 (subsoil + goat manure). The results indicated that compost and manure fertilizer had a significant effect in increasing soil chemical properties (pH, organic carbon content, cation exchange capacity, total-N, available-P, and exchangeable-K), with topsoil treatment having the highest value compared to the subsoil treatment, almost at all parameters. The topsoil treatment + 30 tons ha^{-1} cow manure significantly increased the N-total by 44.44% at 8 and 12 WAA on the control treatment. The topsoil treatment + goat manure 30 tons ha^{-1} significantly increased P-available by 13.63 - 29.74% and exchangeable-K by 40.61 - 62.88% at 4, 8, and 12 WAA against the control treatment. Based on these findings, the best fertilizer method of topsoil treatment + 30 tons ha^{-1} of manure is recommended to increase the soil fertility of the lemon tree soil.

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1. INTRODUCTION

Citrus (*Citrus limon*) is a major global fruit crop (Hippler et al., 2017; Wu et al., 2018). Lemon is a commodity that Indonesian people widely consume. Lemon is rich in vitamin C, which is good for human health. The high demand for lemons is fulfilled by the production of local lemon plantations, one of which is a lemon plantation in East Java. East Java is the province with the largest citrus production in Indonesia. The BPS (2024) reports that in 2024, lemon production in East Java was 36,549 kuintal or around 7.35% of the total national citrus production.

Several factors have caused a decrease in lemon production in East Java, such as extreme climate change, low soil quality, and poor orchard management. Based on other research, the C-organic, total-N, and available-P content of the soil in BSIP Jestro (Citrus and Subtropical Fruit Agricultural Instruments Standardization Agency) was 0.94% (very low); 0.18% (low); and 5.57 mg kg^{-1} (low), respectively (Saraswati et al., 2022). The results of the initial analysis of the soil samples in this study included: pH H_2O; pH KCl; Organic Carbon; N-total; P-total; P-available; exchangeable K; and cations exchange capacity (CEC); the results are: 5.1; 4.5; 1.17%; 0.145%; 592.665 mg.kg^{-1}; 10.33 mg.kg^{-1}; 0.165 cmol kg^{-1}; 26.04 cmol kg^{-1}, respectively. Based on Eviati et al. (2023) criteria, the levels of total-N, available-P, and K-dd are categorized as low, while the CEC of the land is categorized as high. This low nutrient content in the soil can be caused by losses through nutrient leaching, soil erosion and high surface runoff, and lack of application of organic matter to citrus orchards (Huo et al., 2021; Wan et al., 2021).

The subsoil in Inceptisol is known to possess relatively good fertility and generally exhibits good physical properties.

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Organic material is typically placed either on the soil surface close to the tree or beneath the lemon tree canopy. As a result, nutrient uptake is often limited by poor nutrient distribution in the soil profile and by fertilization practices that concentrate nutrients near the soil surface. Meanwhile, the main root system of citrus trees is located at a depth of 0.6-0.9 m in the soil (Alves Júnior et al., 2012), while conventional fertilization is usually confined to the top 10-30 cm, making fertilization in the topsoil less effective. This primarily impacts the upper layer of soil, with minimal influence on the deeper layers. This misalignment between fertilizer placement and root architecture leads to inefficient nutrient absorption, nutrient leaching, and reduced fertilizer use efficiency (Jiang et al., 2018; Komolafe et al., 2019).

Deep placement of organic matter may offer a more effective strategy to address this limitation. One example of deep placement technology is a biopore infiltration hole. The principle of biopores—vertical channels that mimic natural root paths—has been shown to improve water infiltration, aeration, and nutrient transport to deeper soil layers. When organic or inorganic fertilizers are applied into these biopores, nutrient availability in the root zone increases, especially for immobile nutrients such as phosphorus and potassium (Bauke et al., 2017). By applying compost and manure closer to the root zone, particularly in the subsoil, nutrient availability can be enhanced in layers that are more actively exploited by citrus roots, especially during the dry season when topsoil moisture becomes limiting (Jiang et al., 2019; Khalofah et al., 2021). In addition to improving nutrient supply, organic amendments also contribute to better soil structure, increased cation exchange capacity (CEC), and the stimulation of beneficial microbial activity in deeper soil horizons (Ampong et al., 2022; Muktamar et al., 2020).

Previous studies have shown that the application of organic amendments using deep placement technology can significantly improve plant uptake, reduce nutrient leaching (Agyin-Birikorang et al., 2020; Jiang et al., 2018), and improve water-holding capacity (Hanuf et al., 2021). Moreover, the combination of organic matter and deep placement through biopores improves microbial activity and soil structure in subsoil layers, promoting long-term soil fertility. This combination can also increase soil nitrogen (Yunita et al., 2025), increase pH, soil organic carbon, total and available phosphorus (Soemarno et al., 2021).

Excessive fertilizer application results in fertilizer wastes and environmental problems, such as acidification, increasing bulk density, low porosity, and low soil organic matter content (Chandini et al., 2019; Gu et al., 2015; Lv et al., 2020). For environmental problems, chemical fertilizer pollutes surface water, causes eutrophication, N leaching, and produces gas emissions (Liu et al., 2021). Moreover, chemical fertilizer increases production costs and reduces farmers' profits. Several studies have shown that the application of poultry manure (PM) can restore organic content to the soil, reduce production costs, and increase farmer profits (Arianti et al., 2022; Orluchukwu et al., 2019) stated that the combination of PM and residual fungi substrate was suitable for upland rice and was more cost-effective than 15:15:15 NPK fertilization. Combining biochar and inorganic fertilizer increases farmers' profits and reduces production in the second season (Danso et al., 2023).

Reducing the accumulation of pollutants within agricultural systems and abstaining from the utilization of harmful substances are imperative for maintaining a healthy environment (Muktamar et al., 2016). Organic products, derived from natural sources and environmentally friendly, are seen as a viable alternative for sustainable agriculture. Utilizing organic waste materials is a widespread method aimed at enhancing agricultural yields. The positive impact of organic farming on natural resources fosters beneficial interactions within agro-ecosystems, crucial for both agricultural productivity and conservation. There is a growing inclination towards investigating the feasibility of integrating organic fertilizers alongside synthetic ones, given the eco-friendly and cost-efficient nature of this agricultural practice (Mondal et al., 2017). Organic fertilizer can improve soil's physical and chemical properties, such as structure, water retention, nutrients, and cation exchange capacity, and increase biological soil activities, improving yield and quality (Qiu et al., 2021). However, compared to the quick nutrient release of chemical fertilizers, organic fertilizers have low nutrient concentrations, and nutrient release is too slow to support crops quickly (Xiao et al., 2017). Organic fertilizers contain macronutrients available for plants but are slow-released compared to chemical fertilizers. The negative impact of using chemical fertilizers can be avoided by replacing them with organic fertilizers.

Adding organic matter to the soil in lemon orchards has an impact on improving soil quality. Organic matter can stimulate the presence of soil microorganisms and improve soil structure, which was originally massive, to become soil with more stable aggregation and can store more water and nutrients. In addition, the nutrients released from the decomposition of organic matter in the soil can supply the needs of N, P, and K nutrients in lemon trees and reduce the dose of inorganic fertilizers. Applying powdered organic fertilizer at a dose of 10 tons ha^{-1} positively increases the soil's total N-content, which is 60% higher than the application of granular organic fertilizer at the same dose (Saraswati et al., 2022). The results of other studies also show that the application of compost and manure in citrus orchards can improve soil quality and citrus fruit production (Ennab, 2016; Khehra & Bal, 2016; Wan et al., 2021).

The above studies generally placed organic matter on the soil surface near the base of the trunk or under the canopy of lemon trees. This significantly affects the topsoil, while the effect on the subsoil is minimal. Therefore, integrating deep placement techniques with organic matter application may represent an efficient and sustainable fertilization strategy for improving soil fertility and supporting long-term productivity in lemon orchards. The role of subsoil for productive lemon trees is very important, especially during the dry season when the topsoil becomes dry. Therefore, it is necessary to carry out further research regarding the effect of organic matter on the subsoil. This research aims to analyze the impact of organic matter application on enhancing soil nutrient availability and improving soil chemical properties using a pot-scale incubation experiment. This research is a preliminary study on the application of deep placement technology using biopore infiltration holes in lemon plants. This study presents a novel approach by investigating the effects of organic amendments placed at different soil depths in a controlled, pot-scale incubation experiment without plants. By removing plant influence, this method isolates the direct impact of organic matter on the chemical properties of both topsoil and subsoil. The findings from this pilot study provide critical baseline data and offer practical insights for developing more effective fertilization strategies in lemon orchards, particularly those targeting deeper soil layers. A follow-up field experiment is currently underway to evaluate the impact of this approach on lemon tree growth and nutrient uptake under real orchard conditions.

2. MATERIAL AND METHODS

2.1. Time and location of research

The research was conducted from September 2022 to February 2023. The research was carried out in the Greenhouse of the Faculty of Agriculture, Brawijaya University, using Inceptisols soil samples taken from the top layer (0-30 cm) and bottom layer (30-60 cm) of the BSIP Jestro (Citrus and Subtropical Fruit Agricultural Instruments Standardization Agency). The soil moisture content used during incubation is at field capacity conditions, where the topsoil and subsoil are at 66% and 65%, respectively. Laboratory analysis of soil samples was carried out at the Soil Chemistry Laboratory, Soil Science Department, Faculty of Agriculture, Brawijaya University.

2.2. Research methods

This study used a completely randomized design with eight treatments such as P1 (Topsoil + Control); P2 (Subsoil + Control); P3 (Topsoil + Compost); P4 (Subsoil + Compost); P5 (Topsoil + Cow manure); P6 (Subsoil + Cow manure); P7 (Topsoil + Goat manure); P8 (Subsoil + Goat manure) and four replications, so there were 32 (thirty-two) treatment pots. Sampling and observations were made thrice, 4, 8, and 12 weeks after application (WAA). These pots were placed randomly in the greenhouse of the Faculty of Agriculture, Brawijaya University, Malang. The Inceptisols soil samples used were topsoil (0-30 cm) and subsoil (30-60 cm), with as much as 10 kg of air-dry soil per pot. The soil was mixed with organic matter during soil preparation (0 WAA), namely leaf litter compost, cow manure, and goat manure. The leaf litter compost is obtained from the Compost Unit, Agriculture Faculty, Brawijaya University, while the manures are obtained from farmers around BSIP Jestro. The soil and organic fertilizer used were sieved through a 2 mm sieve. The dosage of each organic fertilizer used is 30 ton ha^{-1}, in accordance with the recommended dosage at BSIP Jestro for citrus fertilization. This research is the beginning of using the deep placement method. Deep placement fertilizer is a technology practiced by placing fertilizer directly in the root zone (Komolafe et al., 2019).

This study represents an initial investigation into the use of deep placement technology in lemon-growing soils. In this context, deep placement refers to the application of fertilizers directly into the subsoil, aligning with the rooting depth of lemon trees, which typically reaches up to 40 cm. One example of deep placement is applying fertilizers through biopore infiltration holes, a method adapted to ensure that nutrients are delivered effectively to deeper layers where citrus roots are actively absorbing water and nutrients. Although no plants were grown in this incubation study, the methodology was designed to simulate field-relevant fertilization depth, thereby isolating the impact of organic amendments on the chemical properties of the subsoil.

Although this study refers to the concept of deep placement through biopore infiltration holes, it is important to note that in the current pot-scale incubation experiment, organic fertilizers were mixed uniformly with the soil rather than being applied in localized zones. This methodological difference was intentional and driven by the objective of isolating the direct effect of organic amendments on soil chemical properties at different depths (topsoil and subsoil), without interference from uneven nutrient diffusion or root activity. Uniform mixing allows for more consistent and measurable changes in the soil matrix, which is particularly valuable in controlled, plant-free studies.

However, this approach does not fully replicate the actual conditions of field-based deep placement via biopores, where nutrients are concentrated in vertical columns. As a result, the rate and spatial distribution of nutrient availability in this experiment may differ from those observed under true biopore-based deep placement. In practical applications, biopore placement may lead to slower diffusion but more sustained nutrient availability around the root zone. This study should therefore be viewed as a foundational investigation, with findings that inform the potential effects of organic amendments at specific depths, rather than as a direct simulation of field-level biopore application.

2.3. Laboratory analysis

Parameters observed during the incubation period included pH (H_2O and KCl) (electrometry method), soil organic carbon content (Walkley and Black method), total N (Kjeldahl method), available-P (Bray method), exchangeable-K (NH_4OAc 1N), and cation exchange capacity (NH_4OAc 1N). Observations were made thrice, 4, 8, and 12 weeks after application (WAA). All of the analysis laboratory is based on the standard operational procedure of Eviati et al. (2023).

The results of the initial analysis of the soil samples are presented in Table 1. The results of the topsoil sample analysis showed the value of pH (H_2O), pH (KCl), organic Carbon, N-total, C/N ratio, P-total, P-available, exchangeable K, CEC, and BS (Base saturation) of topsoil and subsoil are acid soil, low organic content, and mostly have low nutrient (Table 1).

2.4. Statistical analysis

The data obtained were analyzed using analysis of variance (ANOVA) at 5% level to determine the effect of treatment on the research variables. If there is a significant effect, then the Least Significant Difference (LSD) test at 5% level is carried out to find out the differences between treatments and at the same time determine the best treatment. The data analysis was carried out using SPSS (Statistical Package for the Social Sciences) software.

Table 1. Preliminary analysis of soil sample

Soil sample	Parameter	Result of analysis	Criteria*
Soil sample from topsoil	pH (H_2O)	5.40	Acid
	pH (KCl)	4.80	Acid
	Organic-C (%)	1.70	Low
	Total N (%)	0.19	Low
	C/N ratio	8.94	Low
	Total P (mg 100 g^{-1})	77.19	Very High
	Available P (mg kg^{-1})	14.67	High
	Exchangeable K (cmol kg^{-1})	0.24	Low
	CEC (cmol kg^{-1})	26.75	High
	BS (%)	24.89	Low
Soil sample from subsoil	pH (H_2O)	4.80	Acid
	pH (KCl)	4.20	Acid
	Organic-C (%)	0.64	Very Low
	Total-N (%)	0.10	Low
	C/N ratio	6.40	Low
	Total-P (mg 100 g^{-1})	41.33	High
	Available-P (mg kg^{-1})	5.99	Low
	Exchangeable K (cmol kg^{-1})	0.09	Very Low
	CEC (cmol kg^{-1})	25.33	High
	BS (%)	26.80	Low

Note: (*) Criteria according to the Eviati et al. (2023)

Table 2. Soil pH (H_2O), Organic carbon, and CEC after organic matter application at topsoil and subsoil

Treatment	Values of soil pH (H_2O) at the week of observation:			Content of C-organic at the week of observation:			Soil CEC value at the week of observation:		
	4 WAA	8 WAA	12 WAA	4 WAA	8 WAA	12 WAA	4 WAA	8 WAA	12 WAA
P1	6.6	6.1 b	6.1 a	1.32 ab	1.38 b	3.25 ab	35.66	40.27 a	53.27 a
P2	6.7	6.0 a	6.0 a	1.09 a	0.68 a	2.90 a	25.24	42.14 a	54.13 a
P3	7.0	6.4 c	6.3 b	1.95 b	2.16 c	3.07 a	31.21	56.46 b	72.75 c
P4	6.7	6.4 c	6.5 c	1.38 ab	2.03 c	3.48 ab	32.30	54.42 b	66.36 b
P5	7.0	6.3 c	6.4 c	1.66 b	2.12 c	4.03 b	30.69	54.62 b	71.40 bc
P6	6.6	6.4 c	6.4 c	1.25 ab	2.23 c	3.38 ab	22.70	55.37 b	67.03 bc
P7	6.5	6.3 c	6.2 b	1.77 b	2.10 c	3.81 b	32.65	54.91 b	72.94 c
P8	6.8	6.2 bc	6.3 b	1.25 ab	1.74 bc	2.95 a	27.11	53.38 b	65.54 b
Note	(ns)	(*)	(**)	(**)	(**)	(**)	(ns)	(*)	(**)

Notes: Criteria according to the Eviati et al. (2023); N: Neutral, AM: Slightly acid. Numbers in the same column followed by the same letter are not significantly different in the 5% LSD Test. WAA: Week After Application. P1: Topsoil (TS); P2: Subsoil (SS); P3: TS + compost; P4: SS + compost; P5: TS + cow manure; P6: SS + cow manure; P7: TS + goat manure; P8: SS + goat manure. TS: Topsoil; SS: Subsoil; ns: not significant; (*) significantly different; (**): Very significantly different.

3. RESULTS

3.1. Soil pH (H_2O) and organic carbon

Based on the analysis of variance, it was found that applying organic fertilizers significantly increased soil pH from topsoil and subsoil in observations 8 and 12 WAA (Week After Applications), but not significantly different in observations 4 WAA (Table 2). The P1 (Topsoil + Control) treatment increased by the initial result from pH 5.4 to 6.6, and the P2 (Subsoil + Control) treatment increased from pH 4.8 to 6.7. All treatments at 8 and 12 WAA showed that the application of organic fertilizer significantly affected increasing pH compared to the control.

At 8 WAA, the P1 (Topsoil + Control) treatment had the lowest pH, which was significantly different from other topsoil treatments, P3 (Topsoil + Compost), P5 (Topsoil + Cow Manure), and P7 (Topsoil + Goat Manure). However, there was no significant difference between P3, P5, and P7. At 12 WAA, the P1 (Topsoil + Control) treatment again had the lowest pH, significantly different from other topsoil treatments: P3 (Topsoil + Compost), P5 (Topsoil + Cow Manure), and P7 (Topsoil + Goat Manure). Furthermore, at 12 WAA, the P5 (Topsoil + Cow Manure) treatment showed a significant difference compared to P3 (Topsoil + Compost) and P7 (Topsoil + Goat Manure), with P5 showing the highest increase in topsoil pH, 5.37% higher than the control (P1). For subsoil treatments (P2, P4, P6, and P8), the P4 (Subsoil + Compost) treatment showed the highest increase compared to the control (P2), although not significantly different from P6 (Subsoil + Cow Manure). At 12 WAA, the P4 treatment had the highest increase in subsoil pH compared to the control (P2), with an increase of 7.81%.

Applying organic fertilizers significantly increased the C-organic content of the topsoil and subsoil in 4, 8, and 12 WAA

(Table 2). The highest value C-organic content in the 4 WAA observations was in the P3 (Topsoil + Compost) treatment (1.95%), the 8 WAA observations the highest value was in the P6 (Subsoil + Cow manure) treatment (2.23%), and the 12 WAA observations the highest value was in the P5 (Topsoil + Cow manure) treatment (4.03%). Overall, topsoil has the highest organic-C content compared to subsoil. The C-organic content of the soil in the P3, P4, P5, P6, and P7 treatments in the 8 WAA observations was very significantly different from the P1 and P2 treatments, with the largest increase in the P6 (Subsoil + Cow manure) treatment, which was 228.50%. At the end of the research (12 WAA), P5 treatment (Topsoil + cow manure) was significant compared to P3 (Topsoil + compost), but not significant compared to P7 (Topsoil + goat manure).

Organic fertilizer applications had a significant effect on topsoil and subsoil CEC in 8 and 12 WAA, but no significant effect in 4 WAA (Table 2). The highest soil CEC value in the 4 WAA observations was found in P1 treatment (Topsoil + Control) (35.66 cmol kg^{-1}), the 8 WAA observations were in the P3 treatment (Topsoil + Compost) (56.46 cmol kg^{-1}) and the 12 WAA observations were in the P7 treatment (Topsoil + Goat manure) (72.94 cmol kg^{-1}).

3.2. Total-N, available P, and exchangeable K content of soil

Based on the results of analysis of variance, the application of organic fertilizers has a very significant effect on increasing the total-N content of topsoil and subsoil in observations of 4, 8, and 12 WAA (Table 3). The highest soil total-N content at 4 WAA was found in treatment P7 (Topsoil + Goat manure) (0.22%), in observations of 8 and 12 WAA were found in treatment P5 (Topsoil + Cow manure) (both of them are 0.26%). Treatment P5 (Topsoil + Cow manure) had the highest total-N content when compared to other treatments with an increase of 43.01% compared to the control treatment P1 (topsoil). Based on basic analysis of soil samples, topsoil has a higher total-N content than subsoil. The total-N content of topsoil as a whole was higher for all treatments than in subsoil. At 12 WAA, the percentage increase was more than 30% compared to the control (P2).

Analysis of variance showed that the application of organic fertilizers significantly affected the available-P content of topsoil and subsoil at observations of 4, 8, and 12 WAA (Table 3). The highest soil available P content was found in the P7 (topsoil + Goat manure) treatment at 4, 8, and 12 WAA observations: 16.51 mg kg^{-1}, 17.63 mg kg^{-1}, and 18.52 mg kg^{-1}, respectively. Soil available P content in the topsoil treatment, including P3, P5, and P7 treatments in the 4, 8, and 12 WAA observations, was significantly different from the P1 treatments. In the subsoil treatment, P6 has significantly different results compared to the P2 treatment (4 WAA). At the end of the research (12 WAA), P7 treatment (Topsoil + goat manure) was significant compared to all treatments.

Based on the analysis of variance, the application of organic fertilizers significantly increased the exchangeable-K content of topsoil and subsoil in observations of 4, 8, and 12 WAA. Based on Table 3, the P7 treatment had the highest exchangeable K content in observations of 4, 8, and 12 WAA: 2.25 cmol kg^{-1}, 2.28 cmol kg^{-1}, and 3.10 cmol kg^{-1}, respectively. At the end of the research (12 WAA), P7 treatment (Topsoil + goat manure) was significant compared to all treatments.

4. DISCUSSION

This research demonstrates that both topsoil and subsoil (deep placement) applications of organic matter can significantly improve soil chemical properties. Topsoil application of cow and goat manure at 30 tons ha^{-1} resulted in the highest immediate nutrient availability, particularly for total-N, available P, and exchangeable K. Applying organic matter, particularly goat manure, cow manure, and compost, showed a notable improvement in several soil chemical characteristics and increased soil fertility. This study reinforces the established role of organic matter in improving soil fertility, while offering new insights into the comparative effectiveness of compost, cow manure, and goat manure in enhancing acidic soil conditions.

Table 3. Content of total-N, available P, and exchangeable K in soil after organic matter application at the topsoil and subsoil

Treatment	Content of total-N in soil at the week of observation:			Content of Available P in soil at the week of observation:			Content of exchangeable K at the week of observation:		
	4 WAA	8 WAA	12 WAA	4 WAA	8 WAA	12 WAA	4 WAA	8 WAA	12 WAA
P1	0.19 bc	0.18 c	0.18 c	14.53 ab	14.40 b	14.27 b	1.60 c	1.56 bc	1.91 bc
P2	0.13 a	0.12 a	0.12 a	13.68 a	12.28 a	12.07 a	0.77 a	0.90 a	1.05 a
P3	0.21 cd	0.21 d	0.21 d	16.22 c	16.30 d	17.32 d	1.90 cd	2.00 d	2.43 c
P4	0.17 b	0.17 bc	0.18 bc	14.69 ab	14.65 bc	15.17 c	1.19 b	1.32 b	1.81 b
P5	0.20 c	0.26 e	0.26 e	16.24 c	17.12 e	17.47 e	1.56 bc	1.63 c	2.96 d
P6	0.15 a	0.19 cd	0.19 cd	14.98 b	15.14 c	15.67 c	1.04 ab	1.16 ab	2.29 c
P7	0.22 d	0.22 d	0.22 d	16.51 c	17.63 e	18.52 f	2.25 d	2.28 d	3.10 d
P8	0.17 b	0.16 b	0.17 b	15.41 bc	15.60 c	15.80 c	1.67 c	1.80 cd	2.00 bc
Note	(**)	(**)	(**)	(*)	(*)	(**)	(*)	(*)	(**)

Notes: Criteria according to Eviati et al. (2023); R: Low; S: Moderate. Numbers in the same column followed by the same letter are not significantly different in the 5% LSD Test. WAA: Week After Application. P1: Topsoil (TS); P2: Subsoil (SS); P3: TS + compost; P4: SS + compost; P5: TS + cow manure; P6: SS + cow manure; P7: TS + goat manure; P8: SS + goat manure. TS: Topsoil; SS: Subsoil; (*) significantly different; (**): Very significantly different.

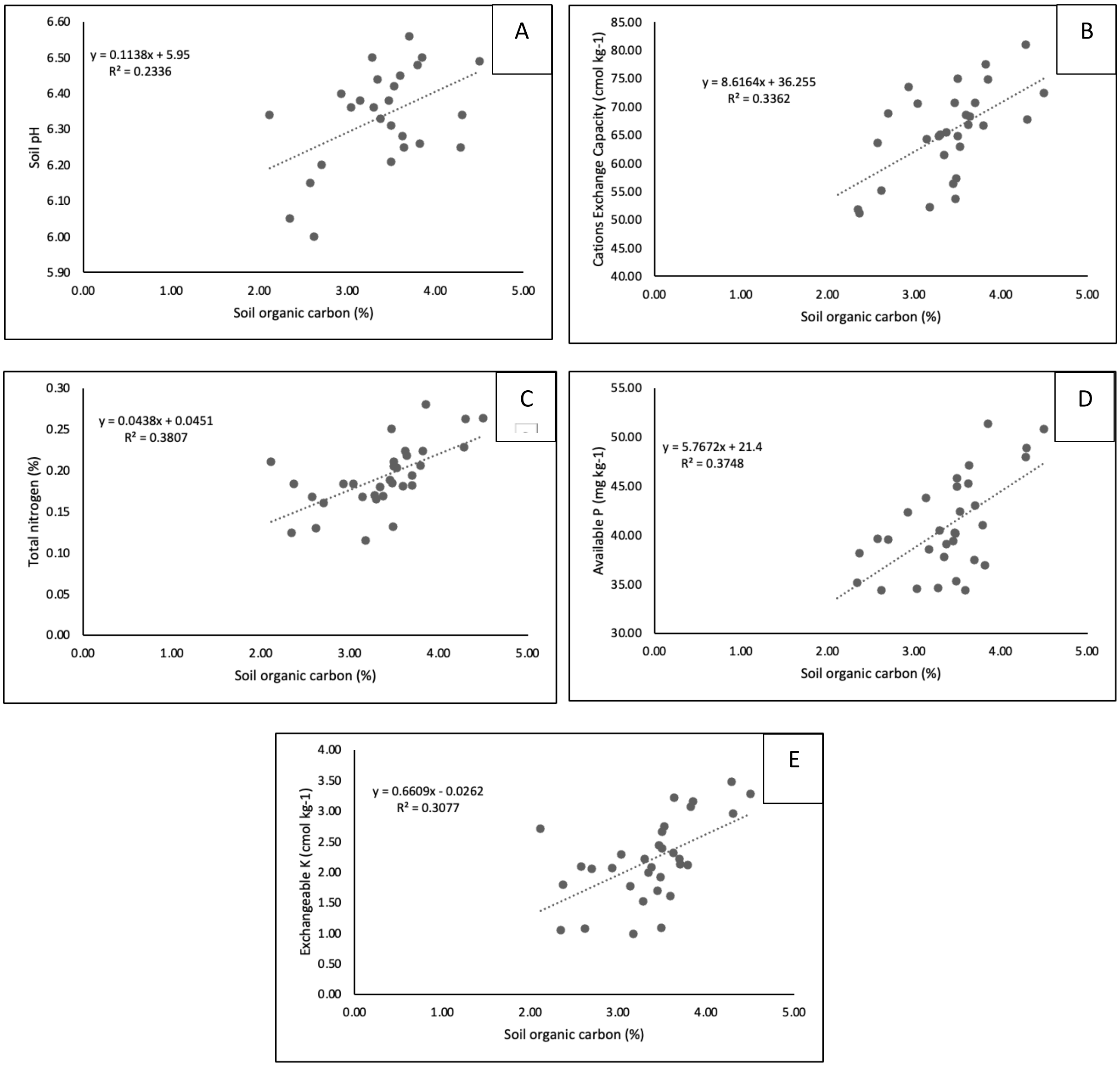

Figure 1. Relationship between soil organic carbon to soil chemistry characteristics after treatment: (A) pH, (B) CEC, (C) total N, (D) available P, and (E) exchangeable K

Although the general benefits of organic matter, such as pH buffering, increased C-organic content, and enhanced nutrient retention, are well-documented, our findings reveal distinct temporal and treatment-specific patterns that carry practical implications for soil management. The association between soil and organic matter application increases soil organic carbon (SOC), which helps explain the improvement in soil pH. As shown in Table 2, treatments P5 (Topsoil + Cow Manure) and P4 (Subsoil + Compost) had a noteworthy effect on soil pH, raising the pH of topsoil and subsoil at 8 and 12 weeks after application (WAA). Although the relationship between soil organic carbon (SOC) and pH was moderate ($R^2 = 0.23$) (Fig. 1), it suggests that SOC plays a supportive, though not exclusive, role in pH changes. The coefficient of determination indicates that variations in soil organic carbon (SOC) can account for 23.36% of the variance in soil pH.

The breakdown of organic matter, which promotes microbial activity and results in the creation of humic compounds, is directly linked to the mechanism underlying this pH improvement. By keeping nutritional cations in the soil solution, these stable compounds serve as pH buffers in addition to improving soil structure (Ampong et al., 2022; Boguta & Sokołowska, 2020; Mostafa et al., 2021). As a result, organic matter-amended soils demonstrated an increase in SOC from low to high criterion. This is in line with research by Simarmata et al. (2016), who found that applying cow manure increased SOC levels by 18.81%, which was higher than the 4.80% increase that compost application caused. These improvements are attributed to the production of humic substances during organic matter decomposition, which not only contribute to soil pH buffering but also enhance cation exchange processes (CEC). In addition to pH. CEC at 8 and 12 WAA was significantly higher in treatments P3 through P8 than in the control groups (P1 and P2). The P7 treatment (Topsoil + Goat Manure) had the highest CEC value, measuring 72.94 cmol kg^{-1} at 12 WAA, which was 36.94% higher than the control. The slow breakdown of organic materials produces negatively charged functional groups that can adsorb nutritional cations, which is responsible for the beneficial effect on CEC. The SOC-CEC relationship ($R^2 = 0.34$)

(Fig. 1) indicates a stronger association than with pH, reinforcing the notion that organic matter contributes to the soil's capacity to retain essential nutrients. Goat manure's superior performance in enhancing CEC and nutrient availability highlights its potential as a multifunctional amendment for nutrient-deficient soils. These results support findings from earlier studies indicating organic materials improve soil CEC and nutrient availability, particularly those that are high in functional groups, such as goat manure (Hartati et al., 2022; Herviyanti et al., 2022; Solly et al., 2020).

Additionally, better nutrient retention or CEC, particularly of nitrogen (N), phosphorus (P), and potassium (K), which are essential for plant growth, is supported by higher CEC. Total nitrogen content also improved substantially, particularly under the cow manure treatment. Cow manure has a higher total N content, 12.2% higher than compost and 2.79% higher than goat manure, making it more effective in terms of nitrogen dynamics. SOC and total N had a positive correlation (R^2 = 0.38) (Fig. 1), indicating that organic amendments increase nitrogen availability by enhancing retention capacity and mineralization processes. While these improvements align with existing studies, our research highlights the timing and specificity of responses based on the type of organic input, with cow manure being more effective for rapid N enhancement. According to research by Holatko et al. (2022) and Santoso et al. (2022), applying cow manure might increase the amount of total nitrogen in the soil from extremely low (0.08%) to extremely high (1.85%). Furthermore, as noted by Jiang et al. (2018), Jiang et al. (2019), and Khalofah et al. (2021), integrating deep placement fertilization technologies can further enhance N-use efficiency and reduce losses from leaching and volatilization, particularly when applied in subsurface layers. Previous results showed that the efficiency of nitrogen fertilization in plants reached 90-135 kg N ha^{-1} from deep placement technology compared to the conventional broadcast application (Agyin-Birikorang et al., 2020; Jiang et al., 2018; Jiang et al., 2019). Likewise, researchers from China and the USA reported higher efficiency and effectiveness of deep placement technology in reducing nitrogen loss and yield increment (Jiang et al., 2018; Jiang et al., 2019).

The application of organic matter also increased the availability of phosphorus, with goat manure having the strongest impact. Throughout all sampling periods, treatment P7 produced the highest P content that was accessible. The correlation between SOC and available P (R^2 = 0.37) (Fig. 1), which is primarily due to microbial activity triggered by organic inputs, emphasizes the contribution of organic matter to P mineralization. These findings emphasize the importance of selecting organic inputs with favorable nutrient release profiles for sustained fertility. Results by Hafiz et al. (2016) and Kaswinarni and Nugraha (2020), who noted increased P availability in soils treated with organic amendments because of microbial-mediated mineralization and the release of fixed P, are supported by the continuous release of available P from decomposing organic matter, especially from goat manure. The breakdown of organic matter and consequent release of K^+ ions is responsible for the steady rise in potassium availability observed across all treatments. By maintaining soil moisture at field capacity, which accelerated mineralization processes, this rise was supported. Goat manure contributed positively to K availability, confirming prior studies and supporting its use in potassium-deficient soils. The observed R^2 of 0.31 between SOC and exchangeable K indicates a moderate relationship, further underlining the complex interaction between organic matter quality, mineralization dynamics, and nutrient availability. In line with research by Sharma et al. (2016) and Situmeang et al. (2019) on the significance of water availability in promoting K mineralization and the hydrolysis of K-bearing minerals, the R^2 value of 0.31 between SOC and exchangeable K indicates a moderately favorable association.

Deep nitrogen fertilizer placement improved nitrogen use efficiency compared to conventional nitrogen fertilizer application methods (Khalofah et al., 2021). Applying organic materials, when combined with other technologies such as deep placement, can further improve soil quality. Deep placement fertilization technology acts as an innovative, effective, and efficient method of fertilizer application. Deep placement fertilization technology is more efficient than conventional fertilization (spread). However, the existence of deep placement technology shows that the application of fertilizers in subsoil can increase the soil quality class. Other fertilizer applications are spreading on the soil surface, "tugal" or dibbling, and other conventional methods. If fertilization is carried out by spreading it on the soil surface, or "tugal", it can cause leaching and evaporation.

The results of this study demonstrate that while topsoil application led to greater immediate nutrient availability (notably in total N, available P, and exchangeable K), deep placement (subsoil application) also contributed positively to soil chemical properties, particularly by increasing soil organic carbon and pH. The significant increase in soil C-organic content (228.50% with cow manure in subsoil) suggests that organic matter applied deeper into the soil profile may have more persistent effects on soil structure and long-term fertility. Although deep placement did not result in the highest available nutrient concentrations in the short term, the observed improvements in C-organic and pH may support nutrient retention and plant uptake over longer periods, especially in systems with deeper root activity such as perennial orchards. These findings support the potential of deep placement as a complementary strategy to surface applications in organic fertilization practices.

The subsoil, often more acidic and nutrient-depleted than topsoil, responded notably well to organic inputs. Treatments incorporating organic matter into the subsoil, such as P2, P4, P6, and P8, demonstrated marked improvements in nutrient availability, highlighting the potential of targeting subsoil layers for fertility enhancement. These improvements are particularly relevant when considering deep placement fertilization strategies, which involve positioning nutrients below the surface layer. By placing organic matter deeper in the soil profile, it helps minimize nutrient loss via leaching or volatilization, while simultaneously enhancing the root zone's nutrient environment.

Although this study provides valuable baseline data, it should be noted that it has certain drawbacks. In order to capture important plant-soil interactions, such as nutrient uptake, rhizosphere activities, and root-associated microbial activity, the experiment was first carried out in a controlled greenhouse without any plants. As a result, results under field settings could not be entirely reflected in the observed changes in soil chemical characteristics. Second, especially in permanent systems like lemon orchards, the pot-based design limits the natural soil heterogeneity, water flow, and root spread that are characteristic of field settings. This could result in an inaccurate assessment of the effects of treatment, particularly regarding lateral transport and nutrient leaching. Third, only the first stage of organic matter breakdown is captured by the 12-week incubation period. It's possible that longer-term nutrient release patterns aren't sufficiently reflected, especially for elements like phosphorus. Furthermore, it is not possible to investigate dose-response relationships or optimize application rates for various field conditions due to the use of a single application rate (30 tons ha^{-1}). Long-term field tests with lemon trees in various environmental conditions should be included in future studies. To confirm and improve the results, these investigations should use deep placement methods, root-soil interactions, and various application rates. In order to create useful and efficient suggestions for improving soil fertility in agroecosystems based on lemons.

5. CONCLUSION

This study demonstrates that both topsoil and subsoil (deep placement) applications of organic matter significantly improve soil chemical properties. Topsoil application of cow and goat manure at 30 tons ha^{-1} resulted in the highest key soil nutrient availability, particularly for total-N, available P, and exchangeable K. In contrast, deep placement (subsoil application) of organic matter, especially cow manure, significantly improved soil pH and C-organic content, indicating potential for longer-term soil fertility enhancement. Although subsoil fertilizer applications did not outperform topsoil applications in terms of short-term nutrient availability, the notable increase in C-organic and pH suggests their role in improving soil fertility and nutrient retention in the long run. This reinforces the value of deep placement fertilization as an innovative and efficient technique, especially for perennial cropping systems such as lemon orchards, where deeper root activity can utilize nutrients stored in the subsoil. These findings emphasize the roles of topsoil and subsoil fertilization. Future research should focus on long-term field trials incorporating different amendment rates and deep placement techniques under real cropping conditions. Understanding root-soil interactions, seasonal dynamics, and dose-response relationships will be critical for optimizing organic matter use and developing practical guidelines for sustainable fertilization practices.

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Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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