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Effects of cricket feces application on soil colloid surface charges and carbon fractions: A nutrient retention improving opportunity in tropical acidic sandy soil

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Abstract

Acidic sandy soils in tropical regions have inherently low nutrient retention due to their highly weathered nature and low organic matter content. Organic amendments, like cricket feces, offer potential for improving soil properties; however, the temporal dynamics of soil charge characteristics under different application methods and rates remain unclear, particularly in variable-charged soils. This study evaluated the effects of application methods (incorporation versus surface placement) and rates (0, 3.13, 6.25, and 12.50 Mg ha^{-1}) of cricket feces on charge characteristics of an acidic sandy soil in Northeast Thailand. An incubation experiment monitored changes in cation exchange capacity (CEC), zero point of net charge (ZPNC), and their related properties. CEC increased with the application rates and was negatively related to ZPNC throughout the experimental period. In the early stage, during 1–5 days, the incorporation treatments produced significantly higher CEC (2.40–3.80 cmol kg^{-1}) than the surface application treatments (2.00–3.50 cmol kg^{-1}), associated with higher pH, organic C, dissolved organic C, and decomposition rate (*k*). In the later stage, by day 45, surface application treatments showed significantly higher CEC (up to 2.73 cmol kg^{-1}) than the incorporation treatments (2.33 cmol kg^{-1}), corresponding with greater dissolved organic C and lower *k*, indicating the effects of organic matter quality affected by the decomposition rate. These findings demonstrated that incorporating cricket feces led to an immediate enhancement of nutrient retention, whereas surface application brought about a more prolonged retention effect.

1. Introduction

Tropical humid soils are typically low in fertility and nutrient retention (Reading et al., 1995; Pincus et al., 2017), causing substantial nutrient losses through leaching (Pendleton, 1943; Finkl, 2008; Sanchez, 2019). These soils are widespread across the tropics, including Sub-Saharan Africa (Sanchez, 2019), South America (Quesada et al., 2011), and Southeast Asia (Noble et al., 2000), particularly in Northeast Thailand (Keerati-kasikorn, 1984; Noble et al., 2000; Suzuki et al., 2007; Vityakon, 2007).

The low nutrient retention capacity of these soils is mainly due to very low organic matter, which decomposes rapidly under humid tropical conditions. In Northeast Thailand, soils are highly weathered and predominantly sandy, similar to those in other tropical soils (Sanchez, 2019). They contain small proportions of low-active surface clays with pH-dependent charges, particularly kaolinite, resulting in low cation exchange capacity (CEC). These charge characteristics govern the soil's physicochemical properties, which are essential for nutrient use efficiency during crop production (Gillman, 2007; Sposito, 2016).

Improving nutrient retention by altering the mineralogy of highly weathered tropical soils is unlikely to be feasible (Lin, 2011); thus, increasing soil organic matter remains the most practical approach. Traditionally, animal manures have been widely used to enhance soil organic carbon, supply essential nutrients, and mitigate acidity (Bayu et al., 2005; Roder et al., 2007; Rayne and Aula, 2020). This practice is common in developed countries, especially in waste management (Hadas et al., 1983; Koutroubas et al., 2016; Obour et al., 2017), and in developing nations where livestock manure is readily available (Banik et al., 2006).

Insect farming has emerged as a promising alternative protein source worldwide (van Huis et al., 2013), with crickets among the most widely cultivated species (Murugu et al., 2021; Kemsawasd et al., 2022). A key by-product of this industry is cricket feces, a nutrient-rich material containing 2.27–2.58% N, 1.55–2.02%

P, and 1.78–2.26% K (Halloran et al., 2017). In Northeast Thailand alone, more than 20,000 cricket farms each produce up to 44 t of feces annually (Halloran et al., 2017). Many countries, including the Thai government, have initiated initiatives promoting cricket farming as an economic enterprise, which is expected to further boost production, raising concerns about waste management. Recycling cricket feces as a soil amendment offers a sustainable solution, supporting the United Nations Sustainable Development Goals by improving soil health and promoting resource efficiency (United Nations, 2015; FAO-UN, 2017). However, its high N content, combined with the tropical humid climate, may accelerate decomposition, potentially influencing soil charge characteristics.

Application methods for the cricket feces amendment can influence decomposition dynamics—incorporating the feces into soil is practical for small-scale systems (Hoc et al., 2016), whereas surface placement is preferred in large-scale farming or to minimize root disturbance (Cox et al., 2021). These contrasting methods may differently affect decomposition and, consequently, soil charge properties. While a few studies have contrasted incorporation and surface placement of organic amendments (Cogger et al., 2008; Cox et al., 2021), none have investigated how charge characteristics evolve over time in acidic sandy soils—typical of tropical humid environments—when treated with cricket feces at varying application rates.

We hypothesized that (i) application methods and rates of cricket feces would alter soil CEC, and (ii) CEC would exhibit positive relations with pH and organic C, with these associations shifting over time. This study, therefore, aimed at determining how contrasting methods and varying rates of cricket feces amendments influence the temporal changes in charge characteristics in an acidic sandy soil of Northeast Thailand, with a focus on pH, organic C, ZPNC, and associated parameters, including EC, available P, and dissolved organic C.

2. Materials and methods

2.1. Soil and cricket feces

Acidic-sandy Ultisol soil was collected from an experimental field at 0–30 cm depth in Sakon Nakhon Rajabhat University (17°11' N, 104°05' E), Sakon Nakhon, Thailand. Cricket (*Brachytrupes portentosus*) feces were sourced from a commercial farm within the same province. Both materials were air-dried and sieved through a 2-mm sieve. Initial properties of the soil and feces can be seen in Autaiwat and Butnan (2024).

2.2. Experimental design and procedure

The soil samples examined in this paper came from the same source as those in Autaiwat and Butnan (2024), but they aimed to assess a different set of objectives and soil properties. A microcosm incubation was conducted under greenhouse conditions (30.4°C, 78.6% RH) using a completely randomized design with three replications. The seven treatments consisted of an unamended control and three application rates (3.13, 6.25, and 12.50 Mg ha^{-1}) of cricket feces, each applied via either incorporation or surface placement.

Each experimental unit consisted of 100 g of air-dried soil in a plastic jar (6.5 cm d × 6 cm h). Feces were applied at 0.15, 0.30, or 0.60 g dry weight jar^{-1} to achieve the low, medium, and high application rates, respectively. Soil moisture was maintained at 65% of the water-holding capacity for the 45-day incubation period by weighing jars every other day and replenishing with deionized water as needed.

Destructive sampling was performed at 1, 3, 5, 10, 15, 30, and 45 days after incubation (DAI), for a total of 147 units. Air-dried samples were analyzed for the charge properties (i.e., CEC and ZPNC), electrical conductivity (EC), organic C, available P, dissolved organic C, and the first-order kinetic constant (k). Notably, the pH values reported here were determined using a different methodology than in Autaiwat and Butnan (2024).

2.3. Laboratory analysis

Soil pH was measured in 1 M KCl at a 1:2.5 soil-to-solution ratio following the method of Butnan et al. (2023), and EC was determined in water at a 1:5 ratio. Organic C was analyzed by wet oxidation using 1 N $K_2Cr_2O_7$, followed by back-titration with 0.5 N $FeSO_4$ according to the Walkley and Black method (Nelson and Sommers, 1982). Available P was extracted with Bray-2 solution (0.1 M HCl + 0.03 M NH_4F) and determined colorimetrically using Murphy's reagent ($(NH_4)_6Mo_7O_{24}\cdot 4H_2O$ + $K(SbO)C_4H_4O_6\cdot 0.5H_2O$ + concentrated H_2SO_4) on a UV-Vis spectrophotometer (Hitachi U-5100, Hitachi High-Tech Corporation, Tokyo, Japan) at 820 nm (Jones, 2001). Dissolved organic C was analyzed following the guidelines of Jones and Willett (2006) by extracting with 0.5 M K_2SO_4, oxidizing with 0.07 N $K_2Cr_2O_7$, and back-titrating with 0.01 N $FeSO_4$.

The CEC was determined by saturating exchange sites with NH_4^+ using 1 N NH_4OAc, displacing NH_4^+ with 10% acidified NaCl, and quantifying NH_4^+ for further CEC calculation by steam distillation (Bremner and Mulvaney, 1982) using a micro-Kjeldahl distillation apparatus (Pro-Nitro S 4002851, JP Selecta, Barcelona, Spain). The ZPNC was determined following Zelazny et al. (1996). Briefly, for each treatment, three soil replicates were combined into a single composite sample, which was then equilibrated in 1 M KCl across a pH range (2.0–7.0) expected to encompass the ZPNC of the soils studied; thus, each treatment included 10 subsamples to cover this pH range. K and Cl were then extracted using 0.5 M $NaNO_3$ for further analysis with a flame atomic absorption spectrometer (Flame AAS novAA® 350, Analytik Jena, Germany) and through titration, respectively. The concentrations of K and Cl were then used to calculate CEC and anion exchange capacity (AEC).

2.4. Calculations and statistical analysis

The ZPNC was defined as the pH where CEC and AEC were equal. The first-order kinetic constant (k) for soil organic C dynamics was calculated as: $k = \ln(w_t/w_0)/t$, where w_t and w_0 are the percentages of organic C remaining at time t and initially, respectively.

The effects of treatments (application methods and rates), time, and their interactions on soil properties, i.e., pH, EC, organic C, CEC, available P, dissolved organic C, and *k* were analyzed using repeated-measures ANOVA. For each sampling interval, treatment effects were assessed with a one-way ANOVA, and treatment means were compared using Tukey's honestly significant difference (HSD) test. Orthogonal contrasts were used to compare application methods (incorporation vs. surface placement). Statistical significance was set at $P \leq 0.05$.

3. Results and discussion

3.1. Temporal changes in soil pH influenced by the application methods of cricket feces

The way cricket feces were applied influenced changes in soil pH over time, a key factor affecting charge characteristics. Orthogonal contrasts and ANOVA confirmed that incorporating the feces into the soil resulted in a significantly higher pH than the surface placement at all application rates (Table 1). This difference was visible in 3 DAI and lasted throughout the entire 45-day study (Fig. 1a *vs.* b). The pH under incorporation ranged from 4.03 to 5.08 across the rates (Fig. 1a), consistently higher than the pH range of 3.96 to 4.86 seen in the surface-applied treatments (Fig. 1b).

The higher pH resulting from the incorporation method was likely due to greater interaction between the feces and soil colloids, which facilitated more exchange reactions (Sposito, 2016; Weil and Brady, 2017). This was especially important given the initially strongly acidic condition (pH 4.06) of the soil studied. In such environments, exchange sites on clay were mainly occupied by H^+ and Al^{3+} ions (Bojórquez-Quintal et al., 2017; Rahman et al., 2024). The toxic levels of Al^{3+} (7.95 mg kg^{-1}) and exchangeable acidity (15.4 mg kg^{-1}) measured in this soil (Autaiwat and Butnan, 2024)—exceeding the >5 mg kg^{-1} Al^{3+} threshold harmful to tropical crops (Sumner and Noble, 2003)—confirm this original chemical setting.

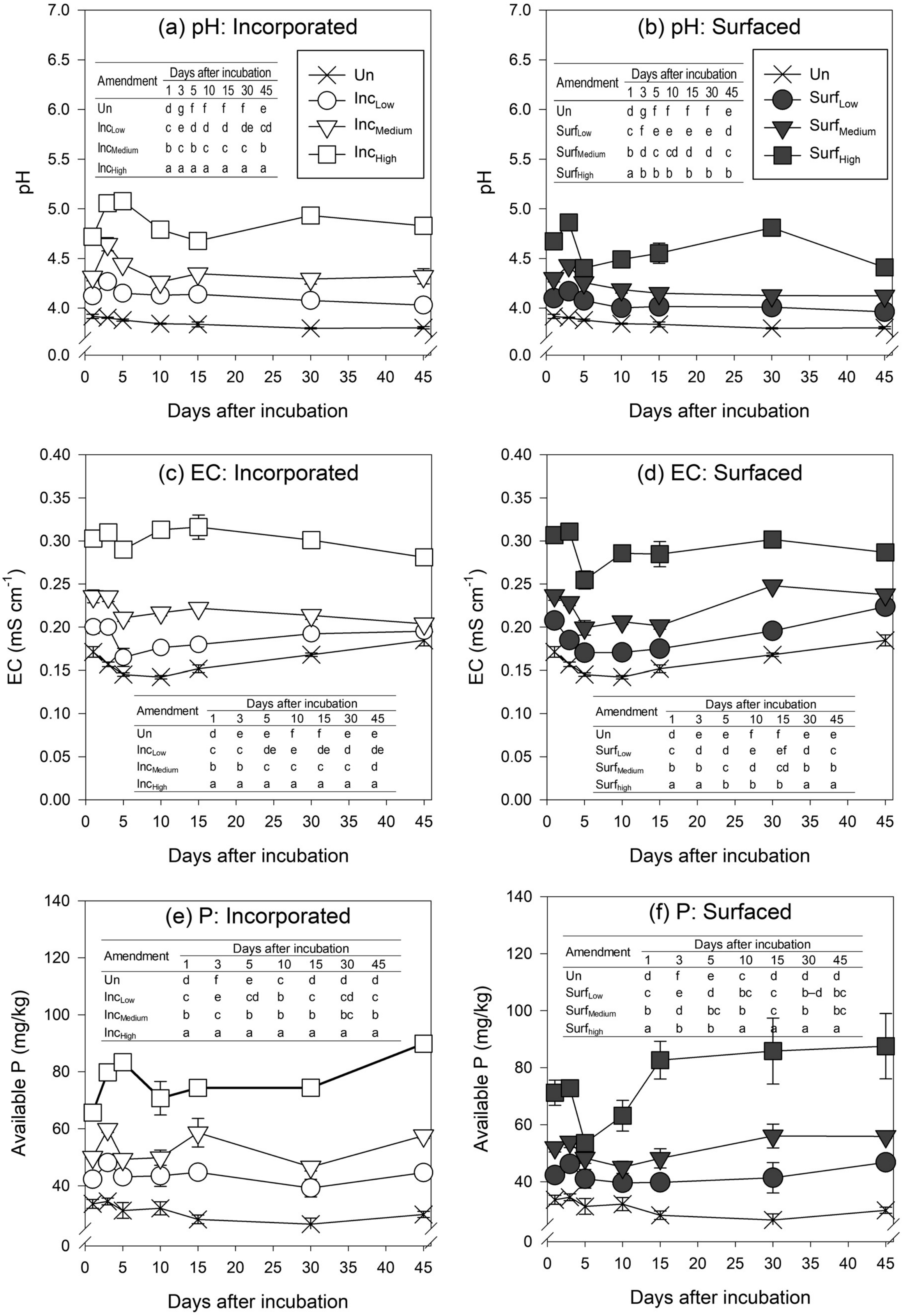
Cations such as Ca^{2+}, Mg^{2+}, and K^+, abundant in cricket feces, were released more efficiently when incorporated into the soil than when surface-applied. This was supported by significantly higher EC—a proxy for ionic strength (Miller and Curtin, 2008)—in incorporated treatments from 3 to 15 DAI (Fig. 1c *vs.* 1d). During this period, EC for incorporated feces ranged from

Table 1

Repeated-measures analysis, one-way analysis of variance (ANOVA), and orthogonal contrast showing the effects of application method and rate of cricket feces on soil pH, organic carbon, cation exchange capacity (CEC), electrical conductivity (EC), available P, dissolved organic carbon (DOC), and the first-order kinetic constant (*k*) in an acidic sandy soil

Source of variance	Period (DAI)	Degree of freedom	*P*-value						
			pH	Organic C	CEC	EC	Available P	DOC	*k*
Repeated-measure analysis									
Treatment (Trt)		6	***	***	***	***	*	***	ns
Time (T)		6	***	***	***	***	ns	***	ns
Trt x T		36	ns	ns	***	*	***	*	***
One-way ANOVA									
Trt	1	6	***	***	***	***	***	***	***
	3	6	***	***	**	***	***	***	***
	5	6	***	***	***	***	***	***	***
	10	6	***	***	***	***	***	**	***
	15	6	***	***	ns	***	***	***	***
	30	6	***	***	*	***	***	***	***
	45	6	***	***	*	***	***	***	***
Orthogonal contrast									
Incorporated *vs.* surfaced	1	1	ns	ns	***	ns	*	ns	ns
	3	1	***	**	**	***	***	ns	**
	5	1	***	**	***	**	***	**	**
	10	1	***	***	ns	***	**	ns	**
	15	1	***	ns	ns	***	ns	ns	ns
	30	1	***	ns	ns	***	**	**	ns
	45	1	***	***	*	***	ns	**	***

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; and ns = not significantly different (*F*-test).



(a) pH: Incorporated

Amendment	Days after incubation						
	1	3	5	10	15	30	45
Un	d	g	f	f	f	f	e
Inc$_{Low}$	c	e	d	d	d	de	cd
Inc$_{Medium}$	b	c	b	c	c	c	b
Inc$_{High}$	a	a	a	a	a	a	a

(b) pH: Surfaced

Amendment	Days after incubation						
	1	3	5	10	15	30	45
Un	d	g	f	f	f	f	e
Surf$_{Low}$	c	f	e	e	e	e	d
Surf$_{Medium}$	b	d	c	cd	d	d	c
Surf$_{High}$	a	b	b	b	b	b	b

(c) EC: Incorporated

Amendment	Days after incubation						
	1	3	5	10	15	30	45
Un	d	e	e	f	f	e	e
Inc$_{Low}$	c	c	de	e	de	d	de
Inc$_{Medium}$	b	b	c	c	c	c	d
Inc$_{High}$	a	a	a	a	a	a	a

(d) EC: Surfaced

Amendment	Days after incubation						
	1	3	5	10	15	30	45
Un	d	e	e	f	f	e	e
Surf$_{Low}$	c	d	d	e	ef	d	c
Surf$_{Medium}$	b	b	c	d	cd	b	b
Surf$_{high}$	a	a	b	b	b	a	a

(e) P: Incorporated

Amendment	Days after incubation						
	1	3	5	10	15	30	45
Un	d	f	e	c	d	d	d
Inc$_{Low}$	c	e	cd	b	c	cd	c
Inc$_{Medium}$	b	c	b	b	b	bc	b
Inc$_{High}$	a	a	a	a	a	a	a

(f) P: Surfaced

Amendment	Days after incubation						
	1	3	5	10	15	30	45
Un	d	f	e	c	d	d	d
Surf$_{Low}$	c	e	d	bc	c	b–d	bc
Surf$_{Medium}$	b	d	bc	b	c	b	bc
Surf$_{high}$	a	b	b	a	a	a	a

Fig. 1. Soil pH (a,b), electrical conductivity (c,d), and available P (e,f), as influenced by the incorporation (Inc) (a,c,e) and surface application (Surf) (b,d,f) of cricket feces at rates of 3.13 ($_{Low}$), 6.25 ($_{Medium}$), and 12.50 ($_{High}$) Mg ha^{-1}. The same lowercase letters within each sampling interval (days after incubation) in the inset tables within each subfigure indicate no significant difference at $P \leq 0.05$ (Tukey's HSD test). Error bars represent standard deviation

0.165 to 0.316 mS cm^{-1} (Fig. 1c), significantly higher than those for surface application (0.170 to 0.311 mS cm^{-1}) (Fig. 1d), as confirmed by orthogonal contrasts (Table 1). These released cations likely displaced and neutralized H^+ and Al^{3+} from soil exchange sites (Hue, 1992).

Aluminum strongly contributes to soil acidity, as acidic conditions promote Al oxide dissolution and hydrolysis, releasing H^+ (Rahman et al., 2024). Neutralization of H^+ and Al^{3+} likely occurred via carbonates of K, Ca, and Mg, which generate bicarbonate upon dissolution, consuming H^+ (Hue, 2022).

Nitrogen transformations, specifically ammonification, may have also played a role in the observed pH changes. This aligns with the net ammonification rates in the previous report (Autaiwat and Butnan, 2024), as increased rates were seen in incorporated treatments during a period that coincided with the peak pHs at 3–5 DAI. The ammonification reaction ($R—NH_2 + H_2O \rightarrow R—OH + NH_3 + H+ \rightarrow NH_4^+$) consumes H^+, thereby directly raising soil pH (Sparks, 2003; Sposito, 2016; Weil and Brady, 2017).

Phosphate dynamics further affected pH. At 3–5 DAI, when pH peaked, the incorporation yielded higher available P than surface application (Table 1, Fig. 1e *vs.* f). For example, at 3 DAI, available P under incorporation was 48.1–79.8 mg kg^{-1} (Fig. 1e) versus 46.2–72.8 mg kg^{-1} under surface application (Fig. 1f). The higher available P in the incorporated soils likely reflects H^+ consumption during phosphate transformations (Barrow and Hartemink, 2023).

Proton (H^+) adsorption by organic functional groups (Lamar et al., 2024) additionally contributed to the pH increases. Carboxyl ($—COO^-$) and phenolic ($—O^-$) groups within the organic matter derived from cricket feces could adsorb H^+ via protonation (Guan et al., 2006; Lamar et al., 2024). This mechanism was more effective under incorporation, as evidenced by significantly higher organic C concentrations in the incorporated soils (Fig. 2a) compared to surface-applied soils (Fig. 2b) at 3–5 DAI (orthogonal contrasts, $P < 0.001$). For instance, at the high application rate, incorporated treatments yielded 4.86 g kg^{-1} organic C at 3 DAI and 4.76 g kg^{-1} at 5 DAI (Fig. 2a), significantly higher than the 4.48 g kg^{-1} and 4.17 g kg^{-1} measured in surface applications (Fig. 2b).

Soil pH peaked at 3 DAI for most treatments of both incorporated (Fig. 1a) and surface-applied soils (Fig. 1b). The high-rate incorporation was the exception, peaking later (pH 5.08 at 3–5 DAI) (Fig. 1a). After a general pH decline and stabilization from 10 DAI onwards, the high-rate treatments diverged: incorporation reached its minimum (pH 4.68) at 15 DAI (Fig. 1a), while surface application minimized earlier (pH 4.40 at 5 DAI) (Fig. 1b). Both exhibited a secondary peak at 30 DAI before a final decline.

The initial rapid increase in pH was likely driven by the dissolution of basic salts (e.g., carbonates and oxides of K, Ca, and Mg) (Carmo et al., 2016; Ozlu and Kumar, 2018) present in the cricket feces. This mechanism was supported by the concurrent peak in EC, which reached 0.310 mS cm^{-1} under incorporation (Fig. 1c) and 0.311 mS cm^{-1} with surface application within the first 3 days (Fig. 1d), indicating a surge of ions in the soil solution. The dissolution of these salts consumed H^+, as shown in the reaction: $CaCO_3 + H^+ \rightarrow Ca^{2+} + CO_2 + H_2O$ (Sparks, 2003; Weil and Brady, 2017), thereby raising the soil pH.

Such pH dynamics were also linked to N transformations shown in the previous study (Autaiwat and Butnan, 2024). The initial pH peak at 3–5 DAI coincided with a period of high net ammonification (consumes H^+), and low nitrification (produces H^+). Subsequently, a decline in pH was accompanied by a shift in these processes: ammonification decreased, while nitrification increased. This pattern was reflected in the observed pH minima, where high-rate surface application dropped to pH 4.40 by 5 DAI (Fig. 1b), while those of the incorporated treatments declined more gradually, reaching minima of pH 4.26 (medium rate, 10 DAI) and 4.68 (high rate, 15 DAI) (Fig. 1b).

A secondary pH rise, occurring only at high application rates, increased from 4.68 to 4.93 in incorporated (Fig. 1a) and from 4.40 to 4.81 in surface-applied (Fig. 1b) between 15–30 DAI. This delayed alkalization likely reflects a mass effect, enabling the prolonged dissolution of slowly soluble salts (e.g., $CaCO_3$) and extended ammonification. A similar two-phase dissolution pattern has been observed in other amendments; for instance, Ulery et al. (1993) demonstrated that ash released alkalinity initially through the rapid dissolution of K and Na oxides, followed by slower $CaCO_3$ dissolution. While ash differed from cricket feces, analogous salts were present in manures, which can contain substantial soluble salts, e.g., 20.6–60.3 g kg^{-1} (Li-Xian et al., 2007), capable of sustaining such gradual pH changes, even though they were also observed in vermicomposts (Lim et al., 2015). This secondary alkalization phase corresponded with concurrent EC trends (Fig. 1c,d). Following an initial decline, the EC at the high application rate began to increase again after 5 DAI, rising to secondary peaks of 0.316 mS cm^{-1} in incorporation at 15 DAI (Fig. 1c) and 0.302 mS cm^{-1} in surface application at 30 DAI (Fig. 1d).

Nitrogen transformation dynamics could also explain the two phases of pH responses observed at high application rates. The initial peak likely arose from the rapid mineralization of labile organic compounds (Noll et al., 2019; Wang et al., 2021), a process strongly supported by the high concentrations of dissolved organic C measured in all treatments (Fig. 4a,b), including the high rates, during the 1–3 DAI, which after declined rapidly to their lowest levels by 5–10 DAI. In contrast, the secondary peak may have been attributed to the delayed ammonification of more stable organic matter coupled with an NH_4^+ toxic effect, where elevated NH_4^+ concentrations inhibited *Nitrosomonas* and suppressed nitrification—a primary source of H^+ production (Rochmah and Mangkoedihardjo, 2020). The mechanism was consistent with Autaiwat and Butnan (2024), who reported sustained NH_4^+-N under incorporation until 15 DAI. Lower NH_4^+-N in surface-applied treatments likely resulted from volatilization losses under elevated pH.

The lack of a second pH peak at low and medium rates (Fig. 1a, b) likely results from insufficient amounts of easily soluble salts and labile organic compounds. The pattern observed with surface application further supports this; it showed an earlier but more gradual secondary pH increase (from 5–30 DAI), while its initial peak declined rapidly. This indicated that reduced soil contact in surface applications lessened the effects of both the initial release of soluble salts and labile compounds and the later release from slower pools.

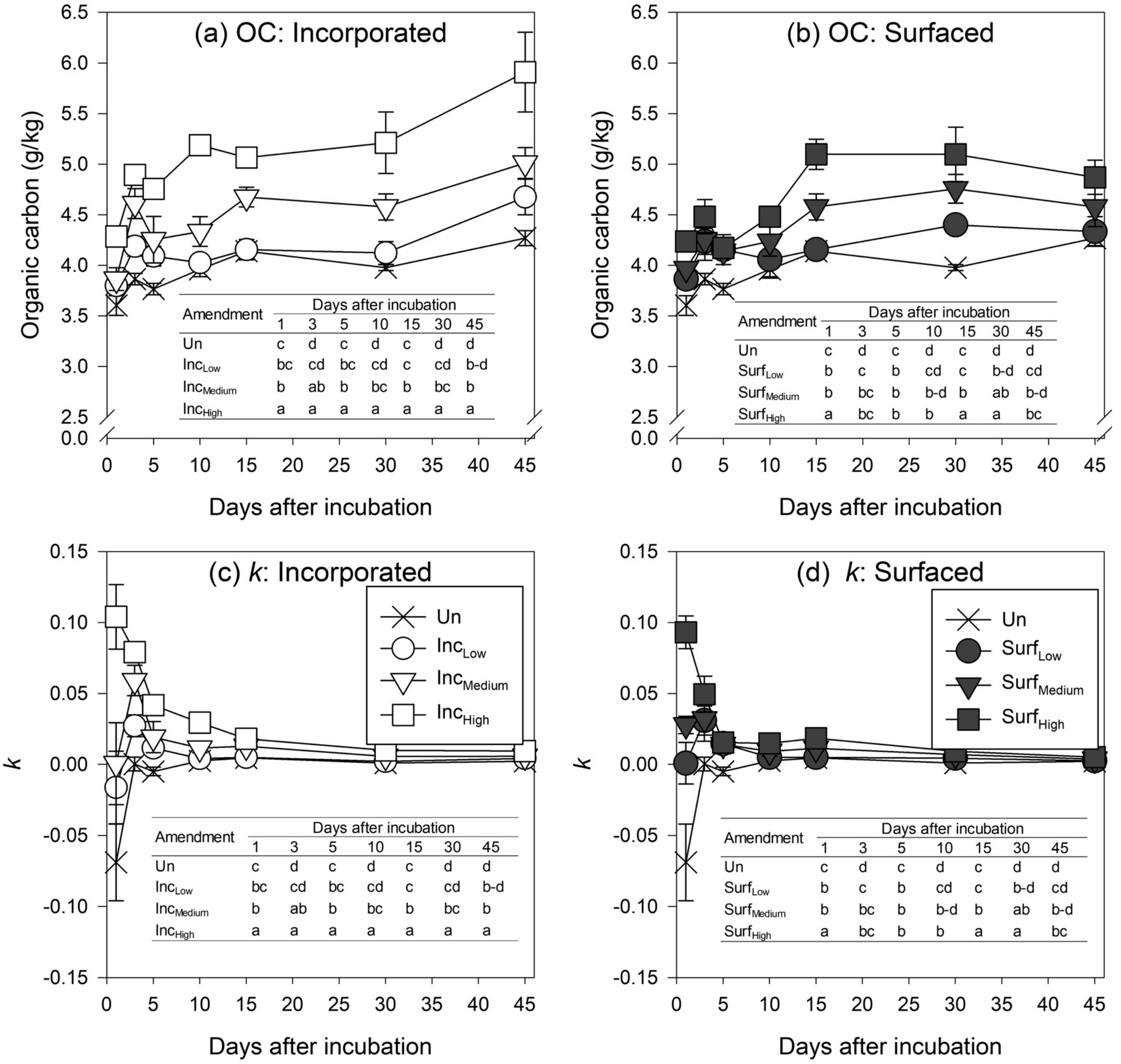


Fig. 2. Soil organic C (a,b) and the first order kinetic constant (*k*) (c,d), as influenced by the incorporation (Inc) (a,c) and surface application (Surf) (b,d) of cricket feces at rates of 3.13 ($_{\text{Low}}$), 6.25 ($_{\text{Medium}}$), and 12.50 ($_{\text{High}}$) Mg ha^{-1}. The same lowercase letters within each sampling interval (days after incubation) in the inset tables within each subfigure indicate no significant difference at $P \leq 0.05$ (Tukey's HSD test). Error bars represent standard deviation

3.2. Effect of time on soil organic C as influenced by application method and rate of cricket feces

Orthogonal contrast analysis revealed that the application method had a significant influence on soil organic C (Table 1). Incorporation of the cricket feces resulted in higher organic C concentrations than surface placement from 3 DAI onwards (Fig. 2a *vs*. 2b). This finding aligns with the studies of Cogger et al. (2008) and Cox et al. (2021), although differences in amendment type and soil properties distinguish this study.

Mean comparisons revealed that the application method had no significant effect on organic C at low and medium rates. However, at the high rate, incorporation maintained significantly higher organic C concentrations (4.29–5.91 g kg^{-1}) (Fig. 2a) than surface placement (4.17–5.10 g kg^{-1}) (Fig. 2b) throughout most of the 45-day incubation. This suggested the mass effect, where a larger input of feces enhanced C retention both directly and by stimulating microbial activity (Jiao et al., 2025). Incorporation improved contact between the amendment and soil microorganisms, promoting the formation of stabilizing agents like glomalin and polysaccharides that enhanced aggregation (Rillig, 2004; Costa et al., 2018). This was consistent with Autaiwat and Butnan (2024), who demonstrated higher microbial activity under incorporation at high rates.

Greater microbial abundance under incorporation contributed to soil organic C through the accumulation of microbial necromass, a key persistent organic pool (Liang et al., 2019; Buckeridge et al., 2020; Li et al., 2024). Furthermore, incorporation facilitated interactions between organic compounds and soil colloids, promoting occlusion within aggregates and providing physical protection that reduced carbon losses (Du et al., 2014; Wang et al., 2017).

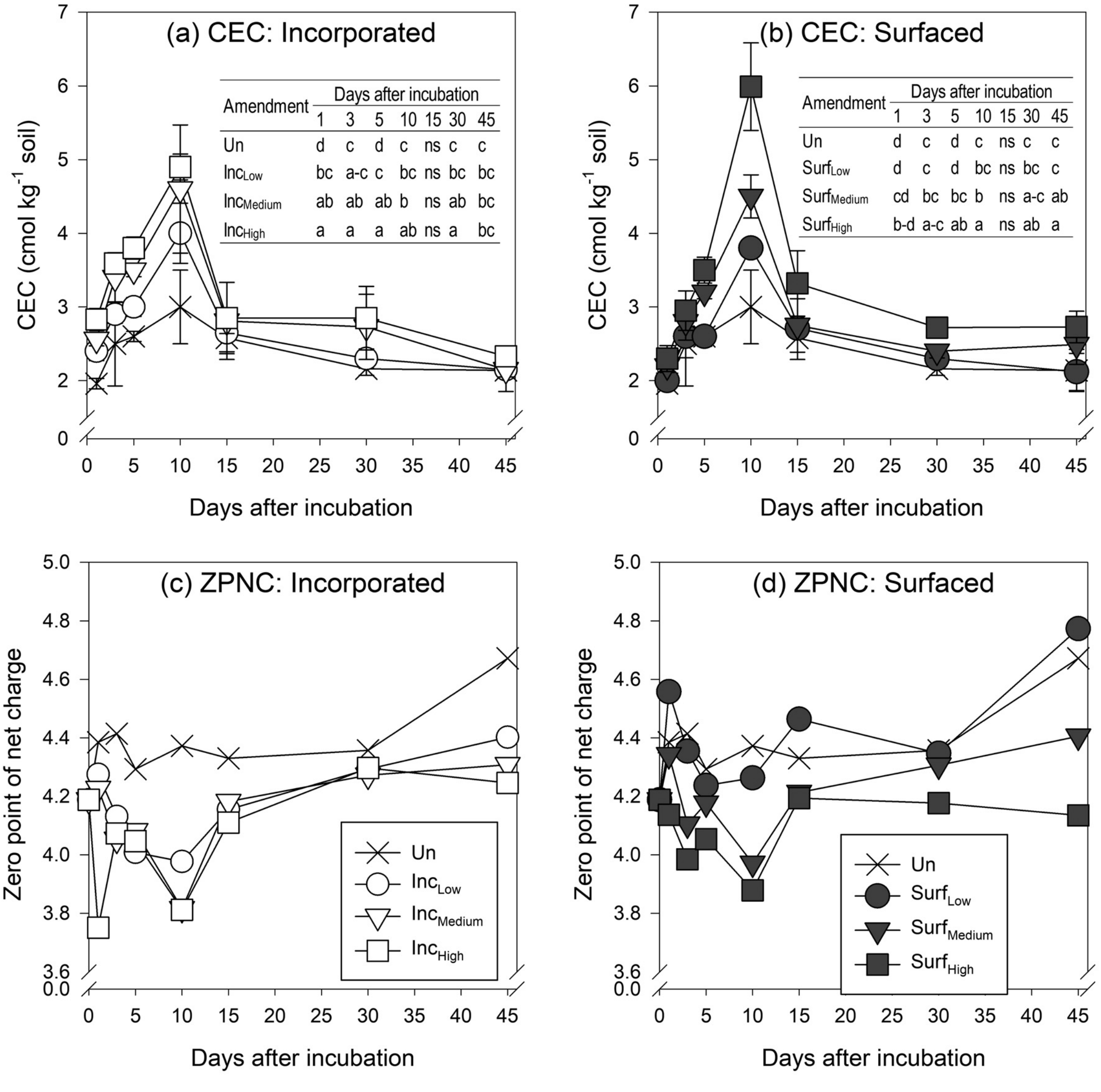
Soil organic C increased over time in all treatments (Fig. 2a,b), including the unamended soils, suggesting contributions from microbial exudates and necromass (Rillig, 2004; Costa et al., 2018). These compounds were reported to be stabilized via occlusion within aggregates and adsorption onto clay minerals and Fe and Al oxides (Kirsten et al., 2021; Islam et al., 2022; Martin Thiagaraja et al., 2025), which were abundant in the highly weathered Ultisol used in this study (Keerati-kasikorn, 1984). The ongoing buildup of these stabilized fractions explained the observed rises, particularly at higher application rates due to greater substrate-induced microbial activity, as supported by Autaiwat and Butnan (2024).

The increase in organic C at 45 DAI compared to 30 DAI, observed only under incorporation (Fig. 2a), suggested sustained C stabilization. In contrast, surface-applied treatments showed stable or slightly declining organic C concentrations (Fig. 2b), likely due to greater exposure of organic matter to oxidation and decomposition when physical protection was limited.

3.3. Cation exchange capacity as influenced by application methods and rates of cricket feces

Orthogonal contrast (Table 1) and multiple comparison analyses revealed a biphasic pattern in CEC (Fig. 3a,b). From 1 to 5 DAI, the incorporation of cricket feces (Fig. 3a) resulted in higher CEC than surface application (Fig. 3b) across all rates (2.40–3.80 *vs.* 2.00–3.50 cmol kg^{-1}). Conversely, this trend was reversed by 45 DAI, when surface application produced a greater CEC.

The CEC (Fig. 3a,b) was inversely related to ZPNC (Fig. 3c,d). For instance, during the 1–5 DAI period, higher CEC under incorporation corresponded with a lower ZPNC (3.98–4.28) (Fig. 3c) compared to surface application (4.02–4.55) (Fig. 3d). Furthermore, increasing the application rate increased CEC while concurrently reducing ZPNC, a pattern that persisted throughout the incubation.



Amendment	Days after incubation						
	1	3	5	10	15	30	45
Un	d	c	d	c	ns	c	c
Inc$_{Low}$	bc	a-c	c	bc	ns	bc	bc
Inc$_{Medium}$	ab	ab	ab	b	ns	ab	bc
Inc$_{High}$	a	a	a	ab	ns	a	bc

Amendment	Days after incubation						
	1	3	5	10	15	30	45
Un	d	c	d	c	ns	c	c
Surf$_{Low}$	d	c	d	bc	ns	bc	c
Surf$_{Medium}$	cd	bc	bc	b	ns	a-c	ab
Surf$_{High}$	b-d	a-c	ab	a	ns	ab	a

Fig. 3. Soil cation exchange capacity (CEC) (a,b) and zero point of net charge (ZPNC) (c,d), as influenced by the incorporation (Inc) (a,c) and surface application (Surf) (b,d) of cricket feces at rates of 3.13 ($_{Low}$), 6.25 ($_{Medium}$), and 12.50 ($_{High}$) Mg ha^{-1}. The same lowercase letters within each sampling interval (days after incubation) in the inset tables within each subfigure indicate no significant difference at $P \le 0.05$ (Tukey's HSD test). Error bars represent standard deviation

The early-phase increase in CEC (Fig. 3a,b) corresponded with elevated pH (Fig. 1a,b) and organic C concentrations (Fig. 2a,b), both of which are key drivers of CEC in variable-charge soils (Sposito, 2016; Weil and Brady, 2017). In the studied Ultisol, which was dominated by Fe and Al oxides and organic matter with minimal contribution from 1:1 clays (<2.5%) (Autaiwat and Butnan, 2024), a rise in pH induced the deprotonation of functional groups on these constituents, exposing negative charges (Essington, 2003; Sposito, 2016)

Contrary to our original hypothesis, surface placement of the feces (Fig. 3a) yielded a higher CEC than the incorporation (Fig. 3b) at 45 DAI, particularly at the high rate, a trend that coincided with a lower ZPNC (Fig. 3c *vs.* d). This finding challenges the conventional positive relationship between CEC, pH, and organic C. The reversal to CEC may be explained by the differential influence of organic C quality (Kopecký et al., 2022). Labile fractions, such as dissolved organic C, have a disproportionately strong effect on CEC in acidic- (Zech et al., 1997), low-organic-matter soils (Mendonça and Rowell, 1996) compared to recalcitrant forms.

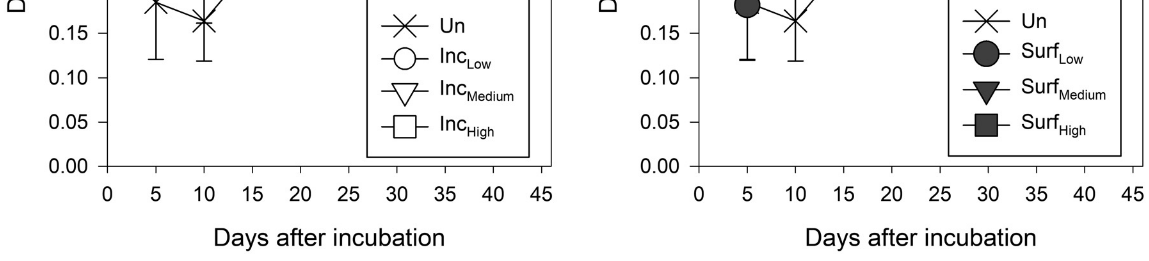
Incorporating the feces accelerated decomposition rates, as shown by higher first-order kinetic constants (k) (Fig. 2c *vs.* 2d), which reduced dissolved organic C availability relative to surface application (Fig. 4a *vs.* 4b). This was seen in orthogonal contrasts (Table 1), which measured significantly lower dissolved organic C under the incorporation compared to the surface placement counterparts at later stages (Fig. 4a *vs.* 4b), e.g., 0.306–0.372 *vs.* 0.352–0.408 g kg^{-1} at 30 DAI, and 0.256–0.424 *vs.* 0.292–0.449 at 45 DAI. The larger dissolved organic C pool in the surface treatments likely increased CEC by supplying higher negatively charged surfaces, while incorporation may have restricted the charge availability through aggregate occlusion.

3.4. Implications for agricultural and environmental sustainability

The methods and rates of applying cricket feces are key factors for managing soil CEC. Incorporating the cricket feces provides a shorter-term increase in CEC, ideal for immediate crop needs for nutrient retention, while surface application fosters a higher, more sustained CEC in the longer term. This temporal trade-off underscores the importance of aligning amendment strategies with specific cropping system objectives, whether for immediate nutrient availability or longer-term benefits.

From a practical standpoint, incorporating feces is most effective for supporting early crop growth stages that require quick nutrient release. In contrast, the surface application aligns with conservation agriculture principles, encouraging longer-term soil fertility without disturbing the soil through tillage. Additionally, the key role of dissolved organic C in regulating CEC highlights that the quality of organic matter is as crucial as its quantity. This insight prompts a shift from simply applying organic amendments to considering their biochemical composition for desired soil functions.

Using cricket feces exemplifies an innovative, circular bioeconomy approach. It establishes a sustainable waste-to-resource pathway for the growing insect farming industry, miti-



Amendment	Days after incubation						
	1	3	5	10	15	30	45
Un	bc	c	c	d	d	e	d
Inc$_{Low}$	bc	bc	b	c	cd	de	d
Inc$_{Medium}$	b	b	ab	c	b	cd	b
Inc$_{High}$	a	a	a	a	bc	a-c	a

Amendment	Days after incubation						
	1	3	5	10	15	30	45
Un	bc	c	c	d	d	e	d
Surf$_{Low}$	c	c	c	bc	b-d	bc	c
Surf$_{Medium}$	b	b	b	bc	b	ab	b
Surf$_{high}$	a	a	ab	ab	a	a	a

Fig. 4. Soil dissolved organic C (DOC), as influenced by the incorporation (Inc) (a) and surface application (Surf) (b) of cricket feces at rates of 3.13 ($_{Low}$), 6.25 ($_{Medium}$), and 12.50 ($_{High}$) Mg ha^{-1}. The same lowercase letters within each sampling interval (days after incubation) in the inset tables within each subfigure indicate no significant difference at $P \leq 0.05$ (Tukey's HSD test). Error bars represent standard deviation

gating environmental risks while simultaneously improving soil health. This practice is especially beneficial for integrated nutrient management in low-input systems. By enhancing the soil's natural nutrient retention capacity, this approach directly supports global efforts to achieve zero hunger and sustain life on land, as campaigned by the FAO-UN. (United Nations, 2015; FAO-UN, 2017).

4. Conclusions

The method and rate of applying cricket feces modulated the CEC of tropical acidic sandy soil through time-dependent relationships with pH, organic C, and ZPNC. Incorporation rapidly elevated pH and organic C, delivering short-term CEC gains for immediate nutrient retention, while surface application conserved dissolved organic C, stabilizing charge properties over longer periods in low-disturbance systems. Practically, incorporation suited early crop stages requiring quick nutrient release, while surface application aligned with conservation agriculture to sustain fertility without tillage. Critically, the quality of organic matter—especially labile fractions like dissolved organic C—governed charge behavior, so both quantity and biochemical composition of amendments needed to be evaluated. Using cricket feces also advanced a circular bioeconomy and integrated nutrient management in low-input systems, enhancing soil health and supporting broader sustainability goals.

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Conflict of interest

The authors declare that they have no conflict of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research did not involve human or animal subjects.

Author Contributions

Somchai Butnan – Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Saranya Autaiwat** – Investigation, Writing – review & editing. **Pranee Sriraj** – Investigation, Methodology, Validation, Writing – review & editing.

All authors read and approved the final manuscript.

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