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Pelletized cricket feces rates affecting nitrogen transformation and vegetable biomass in an acidic sandy soil

Theerapat Chumpla[(1)], **Jenjira Kotama**[(1)] **and Somchai Butnan**[(1)*]

[(1)] Sakon Nakhon Rajabhat University, Faculty of Agricultural Technology, Department of Plant Science, Sakon Nakhon, Thailand.

ABSTRACT: Using pelletized cricket feces as a soil amendment not only enhances soil fertility but also addresses issues of convenient use, reduces dust pollution, and lowers the costs of storage and transportation. This study aimed to evaluate the effects of pelletized cricket feces on nitrogen (N) transformation and fertility of soil, and biomass of a vegetable in an acidic sandy soil. Microcosm and plant bioassay experiments were conducted in a greenhouse, with Chinese kale (*Brassica oleracea* var. alboglabra) used as the plant bioassay. The experiments compared unamended soil (not treated with any soil amendment) with soil amended using either unpelletized or pelletized feces at rates of 3.13, 6.25, and 12.5 Mg ha^{-1}. Compared to unpelletized feces, pelletized feces resulted in decreased soil N mineralization, decreased concentrations of soil NH_4^+-N and NO_3^--N, and diminished availability of N, P, K, Ca, and Mg in both soil and kale tissue, which in turn led to lower biomass of Chinese kale. Despite less beneficial effects than their unpelletized counterparts, pelletized feces could still improve soil fertility and kale yield compared to unamended soil, with benefits increasing at higher application rates. The 12.5 Mg ha^{-1} of unpelletized feces, however, adversely affected Chinese kale biomass due to the antagonistic effect of K on Ca and phytotoxicity of NO_3^-.

Keywords: acid soils, nitrogen mineralization, organic wastes, phytotoxicity, soil amelioration.

*** Corresponding author:**
E-mail: sbutnan@snru.ac.th

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INTRODUCTION

Acidic sandy soils are a global concern, covering about 900 million ha or 50 % of the earth surface (Yost and Hartemink, 2019), and 30-40 % of arable soil (Samac and Tesfaye, 2003). In Northeast Thailand, acidic sandy soils, which make up 80 % of the land (Fujii et al., 2017), pose challenges for crop cultivation due to their infertility (Vityakon, 2007). These soils experience extensive weathering, leaching of basic cations, and accumulation of acidic cations (Samac and Tesfaye, 2003). Rapid decomposition depletes nutrients, especially nitrogen (N), and organic matter, exacerbated by the humid tropical climate (Vityakon, 2007), with global warming further worsening sandy soil degradation (Mehmood et al., 2020).

Enhancing acidic sandy soil with organic amendments, such as animal manure, improves plant nutrient availability, soil organic matter content, and neutralizes acidity (Rayne and Aula, 2020). This approach also addresses the high costs of synthetic fertilizer and supports sustainable agricultural development (Matisic et al., 2024). Cricket feces, in particular, pose beneficial effects for soil fertility improvement (Butnan, 2024). With the growing popularity of crickets as an alternative protein source (Kemsawasd et al., 2022), cricket farming in Northeast Thailand can produce up to 44 Mg of feces per farm annually (Halloran et al., 2017).

Using animal manures, including cricket feces, as soil enhancement has drawbacks due to their dusty nature (Ndegwa et al., 1991) as well as high storage and transportation costs (Cabrera et al., 1994). Pelleting manure can address these issues, reducing water and air pollution, minimizing health risks (Ndegwa et al., 1991), and adding economic value itself (Yang et al., 2020). However, the denser pellets and decreased specific surface area of the feces may reduce the availability of plant nutrients.

While several studies have examined pelletized excrements from cattle (Reza-Bagheri et al., 2011; Zafari and Kianmehr, 2012; Thomas et al., 2017), swine (Zebarth et al., 2005; Pampuro et al., 2017), and poultry (Zebarth et al., 2005; Golden et al., 2006; Lynch et al., 2008; Suppadit and Poungsuk, 2010; Wild et al., 2011; Adeli et al., 2012, 2015, 2016; Sahin et al., 2014), the investigation on pelletized cricket feces, especially regarding N mineralization and soil acidity alleviation, is limited. In addition, there is little information on how different application rates of pelletized cricket feces affect soil and plants in acidic sandy soils. To our knowledge, this study is the first report to explore pelletized cricket feces as a soil amendment, aiming to determine the optimal timing and application rates for maximizing crop yields.

The study hypothesized that (i) pelletizing cricket feces would decrease soil N mineralization rate, (ii) depress vegetable biomass through lower nutrient availability, and (iii) reduce the capacity of soil acidity amelioration compared to the unpelletized counterparts. This study aimed to (i) examine the influence of the application rates of pelletized cricket feces on soil N transformation and the temporal changes in soil acidity, and (ii) assess the effects of the rates of the feces on soil physicochemical properties and vegetable biomass in an acidic sandy soil.

MATERIALS AND METHODS

Soil and cricket feces

Two experiments were conducted: a microcosm and a plant bioassay. The focus was on acidic sandy Ultisols from Northeast Thailand. Soil was collected from the top 0.00-0.15 m layer using a spade, with samples randomly taken from five locations within the coordinates 17° 11’ 09” N, 104° 05’ 18” E to 17° 11’ 10” N, 104° 05’ 17” E at the Faculty of Agricultural Technology, Sakon Nakhon Rajabhat University, Sakon Nakhon, Thailand. Soil for the microcosm experiment was gathered in July 2022, while that for the plant

bioassay experiment was collected in November 2022. Soil samples were dried in the shade and sieved through a 2-mm mesh for further use in the experiments. The initial soil properties are shown in table 1.

The feces used in both experiments were sourced from *Brachytrupes portentosus*, which was obtained from a farm in Mueang district, Sakon Nakhon, Thailand, in July 2022. The feces were air-dried, cleaned of non-faecal substances, and sifted through a 2-mm mesh. They were divided into unpelletized feces which were only passed through the sieve with no further processing, and the pelletized counterpart, which owned approx. 6-mm diameter. Both types of feces were used immediately in the microcosm experiment, while some were stored in a sealed plastic box at room temperature for four months prior to the plant bioassay launched. The initial characteristics of each type of cricket feces are detailed in table 1.

Experimental design and management

For both microcosm and plant bioassay experiments, a completely randomized design with three replications was employed. Treatments included an unamended soil, which refers to soil not treated with any amendments, and six amended soils, treated with either unpelletized or pelletized cricket feces at three rates: 3.13 (low), 6.25 (medium), and 12.5 (high) Mg ha^{-1}, resulting in a total of seven treatments. These application rates were based on the generally recommended rate for organic fertilizers used in sandy-textured soils in Thailand, set at 6.25 Mg ha^{-1}.

Table 1. Initial properties of soil, cricket feces and their pelletized form used in the microcosm and plant bioassay experiments

Properties	Soil		Unpelletized cricket feces		Pelletized cricket feces	
	Microcosm	Bioassay	Microcosm	Bioassay	Microcosm	Bioassay
Soil particle distribution (g kg^{-1})						
Sand	791	761	–	–	–	–
Silt	184	214	–	–	–	–
Clay	25	25	–	–	–	–
Soil texture	Loamy Sand	Loamy Sand	–	–	–	–
BD (Mg m^{-3})	1.38	1.44	0.37	0.43	0.27	0.28
WHC (% w w^{-1})	32.6	32.3	–	–	–	–
pH(H_2O)	4.64	4.10	6.96	6.40	6.58	6.25
EC (mS cm^{-1})	0.284	0.111	12.5	12.3	12.3	19.1
CEC ($cmol_c$ kg^{-1})	2.58	3.12	69.8	90.4	56.0	81.5
OC (g kg^{-1})	3.93	3.34	181	179	179	180
TN (g kg^{-1})	0.24	0.12	6.76	7.08	5.33	11.0
NH_4^+-N (mg kg^{-1})	0.54	4.08	110.1	322.2	30.5	139.7
NO_3^--N (mg kg^{-1})	0.42	2.53	1.17	6.77	2.57	4.08
P (mg kg^{-1})	21.7	25.0	6,573	1,570	6,296	939
K (mg kg^{-1})	25.5	25.0	8,438	11,372	10,803	9,267
Ca (mg kg^{-1})	104	200	2,169	5,858	2,041	3,475
Mg (mg kg^{-1})	11.8	23.1	650	982	1,146	828
Na (mg kg^{-1})	10.0	8.1	1,007	1,825	1,126	1,654
Al (mg kg^{-1})	9.30	11.33	nd	nd	nd	nd
EA (me 100 g^{-1})	0.821	0.189	nd	nd	nd	nd

pH(H_2O) using soil: solution ratio equal to 1:2.5. nd: not detectable; BD: bulk density; WHC: water holding capacity; EC: electrical conductivity; CEC: cation exchange capacity; OC: organic C; TN: total N; and EA: exchangeable acidity.

Microcosm experiment

The microcosm experiment was conducted during August and September 2022 in a greenhouse equipped with an evaporative cooling system at the research facility of the Faculty of Agricultural Technology, Sakon Nakhon Rajabhat University, Thailand, with an average air temperature of 30.4 °C and 78.6 % humidity.

One hundred grams of soil were placed in a cylindrical polypropylene jar (5.2 cm *d*, 3.8 cm *h*, and 80.7 cm^3 *v*). The lid of the jar was removed during the experiment. Either unpelletized or pelletized, cricket feces were mixed at low, medium, and high rates (0.151, 0.302, and 0.604 g dry weight jar^{-1}) based on an initial soil bulk density of 1.38 g cm^{-3}. The unpelletized cricket feces, with 6.81 % moisture, were then adjusted to 0.161, 0.322, and 0.644 g for low, medium, and high rates, respectively. Pelletized feces were oven-dried at 65 °C for 72 h due to the impacts of heavy rainfall and high humidity. After oven-drying, the pelletized feces were in a normal condition, with their working weight matched their dry weight.

After mixing both types of feces into the soil, their moisture content was maintained at 65 % of the water-holding capacity (WHC) (32.6 % v w^{-1} using 21.2 mL of distilled water for each jar) throughout the experiment by weighing the jars every other day. The experiment lasted 45 days, corresponding to the growth period of the plant bioassay, with regular soil sampling for NH_4^+, NO_3^-, microbial activity, and pH. Sampling involved a destructive procedure, meaning that the entire soil sample from each jar was used, and the sampled jars were subsequently removed. Samples were collected at seven time intervals: 1, 3, 5, 10, 15, 30, and 45 days after the feces incubation, with each interval comprising the seven treatments and three replications, resulting in a total of 147 jars.

Plant bioassay experiment

The plant bioassay experiment was conducted from December 2022 to January 2023 under greenhouse conditions similar to those of the microcosm experiment, averaging 30.2 °C and 53.4 % humidity. Three kilograms of dry soil were placed in a pot (18 cm top *d*, 13.5 cm bottom *d*, 14.3 cm *h*, and 2805 cm^3 *v*), which had drainage holes at the base, along with a tray placed underneath. The soil was mixed thoroughly with either unpelletized or pelletized cricket feces at low, medium, and high rates (4.34, 8.68, and 17.36 g dry weight), based on an initial soil bulk density of 1.44 g cm^{-3}.

Unpelletized cricket feces with 0.94 % moisture content were adjusted to 4.38, 8.76, and 17.52 g for low, medium, and high rates, while pelletized feces with 3.01 % moisture content were adjusted to 4.47, 8.94, and 17.88 g, respectively. The soil was incubated at 65 % WHC for 15 days before seedlings were transplanted, maintaining this moisture level throughout.

Chinese kale (*Brassica oleracea* var. alboglobra) was used for the bioassay. Seedlings were grown and nursed in plug trays for 15 days, after which one seedling was transplanted into each pot. Soil moisture content was maintained at 65 % WHC throughout the experiment by weighing the pots daily. Kale was harvested 45 days after planting. Shoot fresh weight was measured and then oven-dried at 65 °C till reaching a constant weight for the dry-weight assessment. Shoot biomass was thereafter ground and sieved through a 1-mm mesh for further tissue elemental content analysis.

On the day of kale harvesting, soil bulk density was assessed, and fresh soils were also sampled for NH_4^+, NO_3^-, and microbial activity analyses. The remaining soil was left to be air-dried and sieved through the 2-mm mesh for simultaneous root sampling and preparation for further analyses of the relevant soil properties. Root samples were subsequently cleaned and oven-dried at 65 °C till constant weight was achieved, and their dry weight was recorded.

Laboratory analysis

Soil particle size distribution was analyzed using the pipette method (Kroetsch and Wang, 2008). Soil bulk density was measured using the core method (Pansu and Gautheyrou, 2006). As for both soil and cricket feces, the following procedures were employed. The pH and electrical conductivity (EC) were determined using 1:2.5 and 1:5 ratios (material:water). Organic C was measured using the Walkley and Black method, following the procedures described in Nelson and Sommers (1982). Mineral N (NH_4^+ and NO_3^-) was extracted with 2 mol L^{-1} KCl and quantified using the stream distillation method (Stevenson, 1982) with a micro-Kjeldahl apparatus (Pro-Nitro S 4002851, JP Selecta, Barcelona). Phosphorus was extracted with Bray-2 solution and measured using a UV-Vis spectrophotometer (Hitachi U-5100, Hitachi High-Tech Corporation, Tokyo) at 820 nm according to Jones (2001). Potassium, Ca, Mg, and Na were determined using 1 mol L^{-1} NH_4OAc extraction at pH 7 and quantified with a flame atomic absorption spectrometer (Flame AAS novAA® 350, Analytik Jena, Germany). Exchangeable Al and acidity were extracted with 1 mol L^{-1} KCl and measured by the titration method (Pansu and Gautheyrou, 2006). Cation exchange capacity (CEC) was determined by saturating soil and feces with NH_4^+ derived from 1 mol L^{-1} NH_4OAc, and NH_4^+ was then extracted with 10 % acidified NaCl and determined using the distillation method (Pansu and Gautheyrou, 2006). Microbial activity was assessed using the fluorescein diacetate (3',6'-diacetylfluorescein, FDA) hydrolytic activity method following Green et al. (2006). In brief, 0.5 g of fresh soil was mixed with 60 mmol L^{-1} FDA lipase substrate and incubated at 37 °C for 3 h to allow microorganisms to convert FDA into fluorescein, a fluorescent compound. The fluorescein was extracted through centrifugation followed by filtration, and the extract was measured for fluorescein content using the UV-Vis spectrophotometer at 490 nm.

Shoot tissue contents of N, P, K, Ca, and Mg were extracted using the perchloric wet digestion method following Miller (1988). Then, tissue N was measured using the distillation method (Horneck and Miller, 1998). Tissue P was determined using UV-vis spectrophotometry, while cations were determined by the flame AAS.

Data calculations and statistical analysis

The cation ratios of soil structure stability (CROSS) were calculated using equation 1 (Rengasamy and Marchuk, 2011).

$$\mathrm{CROSS} = ([\mathrm{Na}] + 0.56[\mathrm{K}])/(([\mathrm{Ca}] + 0.60[\mathrm{Mg}])/2)^{1/2} \quad \text{Eq. 1}$$

in which: [Na], [K], [Ca], and [Mg] are concentrations in $cmol_c$ kg^{-1}.

Net N mineralization was calculated by summing NH_4^+-N and NO_3^--N concentrations for each treatment and subtracting the control (unamended treatment). Elemental uptake in the kale shoot was determined by multiplying shoot tissue elemental content by shoot dry weight.

Analysis of variance was used to evaluate the effects of pelletized cricket feces on soil N transformation, microbial activity, soil pH, and other relevant soil properties, as well as kale biomass and tissue nutrient contents. Tukey's honestly significant difference (HSD) test was used in multiple comparisons. A significant difference was at $p \leq 0.05$.

RESULTS

Microcosm experiment: the effects on soil N transformation, microbial activity, and pH

Concentrations of soil NH_4^+-N (Figures 1a *vs*. 1b) and NO_3^--N (Figures 1c *vs*. 1d), net N mineralization rates (Figures 1e *vs*. 1f), microbial activity (Figures 2a *vs*. 2b), and pH (Figures 3a *vs*. 3b) were generally lower in pelletized than unpelletized feces across all intervals. Exceptions were shown on specific days, i.e., days 1 and 45 for NH_4^+-N, NO_3^--N, and net N mineralization rates; day 10 for NH_4^+-N; and days 1 and 30 for microbial activity. In comparison to unamended soil, the application of cricket feces, whether unpelletized or pelletized, resulted in increased NH_4^+-N, NO_3^--N, net N mineralization rates, microbial activity, and pH across nearly all intervals.

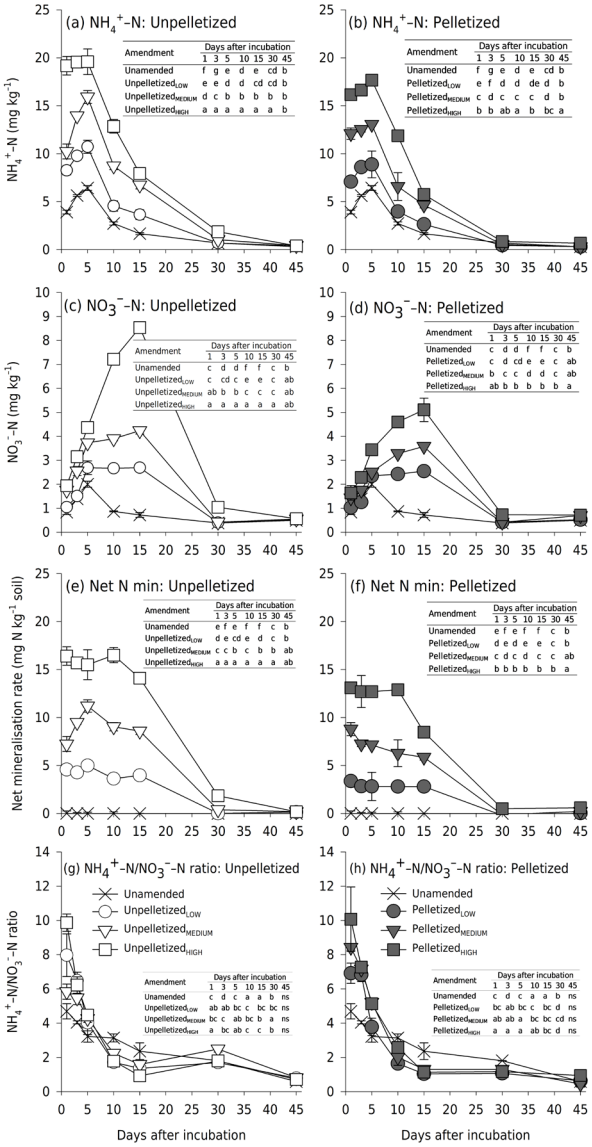

Figure 1. Soil N status as influenced by varied application rates of unpelletized and pelletized cricket feces in the microcosm experiment: NH_4^+-N concentrations in (a) unpelletized and (b) pelletized cricket feces; NO_3^--N concentrations in (c) unpelletized and (d) pelletized cricket feces; net N mineralization rates in (e) unpelletized and (f) pelletized cricket feces; and ratios of NH_4^+-N/ NO_3^--N concentrations in (g) unpelletized and (h) pelletized cricket feces. Low, medium, and high, which are part of the treatment description in the inset tables, refer to application rates of unpelletized and pelletized cricket feces at 3.13, 6.25, and 12.5 Mg ha^{-1}. Similar letters in the same columns for each sampling time interval (days after incubation) across unpelletized and pelletized cricket feces indicate no statistically significant differences at $p \leq 0.05$ (Tukey's HSD test).

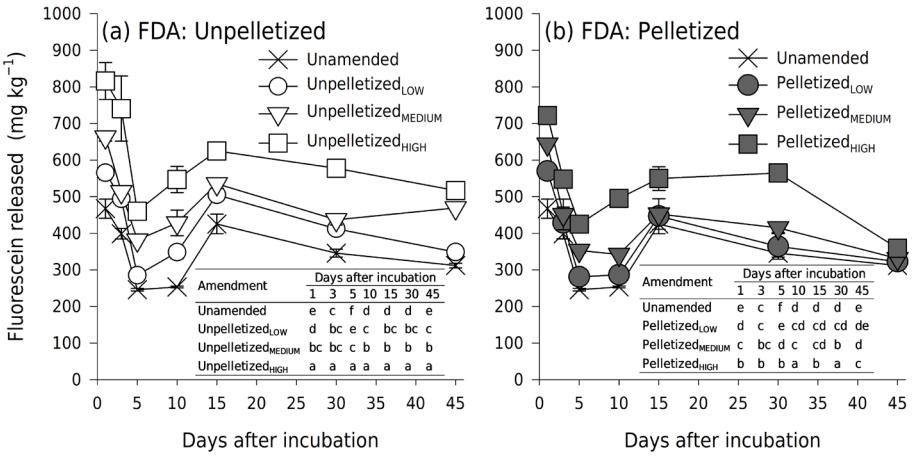

Figure 2. Fluorescein release indicates microbial activity as influenced by varied application rates of (a) unpelletized and (b) pelletized cricket feces in the microcosm experiment.

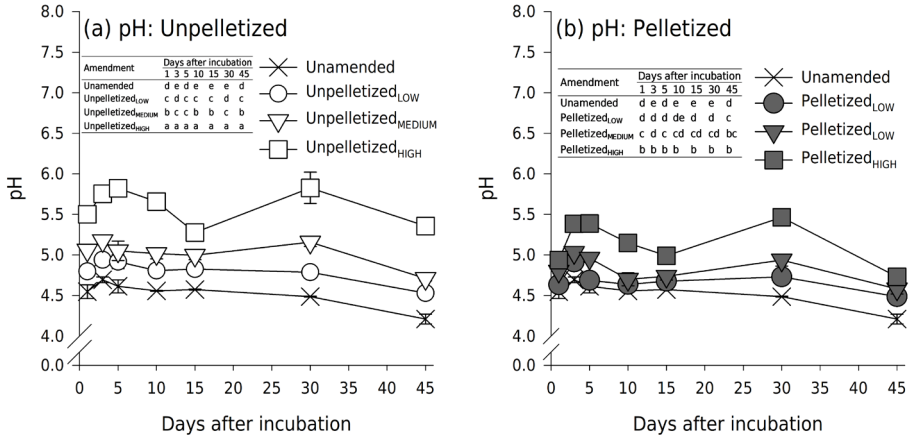

Figure 3. Soil pH as influenced by varied application rates of (a) unpelletized and (b) pelletized cricket feces in the microcosm experiment.

In both unpelletized and pelletized cricket feces, NH_4^+-N concentrations (Figures 1a and 1b) peaked on day 5 (8.9-19.6 mg kg^{-1} of NH_4^+-N), then declined rapidly until day 15 (2.6-7.9 mg kg^{-1} of NH_4^+-N), followed by a gradual decrease till day 45 (0.3-0.7 mg kg^{-1} of NH_4^+-N). Soil NO_3^--N concentrations (Figures 1c and 1d) increased until day 15 (2.5-8.5 mg kg^{-1} of NO_3^--N), peaked, then decreased rapidly to day 30 (0.4-1.0 mg kg^{-1} of NO_3^--N), and stabilized thereafter (0.5-0.7 mg kg^{-1} of NO_3^--N). Net N mineralization rates in treatments amended with both types of cricket feces (Figures 1e and 1f) were generally high during the first 15 days (ranged 2.8-14.1 mg kg^{-1} of N on day 15), except for their medium rates. Net N mineralization rates of the medium rates then decreased between days 15 (8.6 and 5.8 mg kg^{-1} for unpelletized and pelletized) and 30 (0.4 and -0.1 mg kg^{-1} of N for unpelletized and pelletized) before gradually stabilizing (0.2 mg kg^{-1} of N for both unpelletized and pelletized on day 45).

The NH_4^+-N/NO_3^--N ratios were not clearly defined between treatments (Figures 1g and 1h). However, all application rates for both unpelletized and pelletized treatments displayed a similar temporal pattern, showing a rapid decline from day 1 (5.8-10.1) to day 15 (0.9-1.6), followed by stability until day 45 (0.5-0.9).

Microbial activity, as indicated by fluorescein release, from both unpelletized (Figure 2a) and pelletized (Figure 2b) feces treatments generally increased with higher application rates. Across all treatments, microbial activity rapidly decreased from days 1

(467-816 mg kg^{-1}) to 5 (246-460 mg kg^{-1}), reached a minimum between days 5 and 10 (253-547 mg kg^{-1}), increased from days 10 to 15 (425-625 mg kg^{-1}), and then gradually declined until day 45 (312-517 mg kg^{-1}).

Applying cricket feces, whether unpelletized or pelletized, generally increased soil pH (Figures 3a and 3b), with unpelletized feces generally resulting in higher pH at equal application rates. Soil pH peaked on day 5 for all treatments (pH 4.61-5.82), continued to rise until day 10 for the high rates (pH 5.66 for unpelletized, 5.15 for pelletized), then declined by day 15 (pH 4.57-5.28), increased again from days 15 to 30 (pH 4.49-5.83), and finally decreased from days 30 to 45 (pH 4.21-5.36), with more pronounced changes observed at higher application rates.

Soil organic C concentrations in both types of cricket feces, as well as total N concentrations in unpelletized feces, increased with higher application rates (Table 2). Unpelletized feces raised soil organic C by 3.92-4.33 g kg^{-1} and pelletized feces by 3.86-4.32 g kg^{-1} from low to high rates, compared with unamended soil at 3.41 g kg^{-1}. Total N increased by 0.197-0.233 g kg^{-1} for unpelletized and 0.181-0.200 g kg^{-1} for pelletized feces from low to high rates, compared with unamended soil at 0.161 g kg^{-1}.

Plant bioassay experiment: Effects on soil properties and Chinese kale biomass

Increasing the application rates of both unpelletized and pelletized cricket feces generally increased pH, EC, CEC, organic C, total N, P, K, Ca, Mg, Na, and microbial activity (Table 3). However, there were decreases in NH_4^+-N, Al, and exchangeable acidity, with the rates increased. Interestingly, soil bulk density increased unexpectedly with higher application rates of both types of feces.

Shoot tissue contents of N, P, and Na tended to increase with higher application rates for both feces types, while K with unpelletized feces and Mg with pelletized feces (Table 4). Meanwhile, the K/Ca ratio tended to increase, and the Ca/Mg ratio tended to decrease with increased rates of unpelletized feces (Table 5). No significant differences were observed in the K/Ca and Ca/Mg ratios for pelletized feces. In unpelletized feces, the K/Mg ratio decreased at medium application rates but increased at high rates, whereas it tended to decline with higher rates of pelletized feces. To further investigate the antagonistic effects among cationic nutrients, regression analysis was conducted, revealing a significant effect of tissue K on tissue Ca (Figure 4a). However, no interaction effects were found between tissue K and tissue Mg (Figure 4b) or between tissue Ca and tissue Mg (Figure 4c).

Table 2. Soil organic carbon and total N concentrations of the microcosm experiment

Amendment	OC	TN
	g kg^{-1}	
Unamended	3.41 d	0.161 c
$Unpelletized_{LOW}$	3.92 bc	0.197 b
$Unpelletized_{MEDIUM}$	4.13 ab	0.199 b
$Unpelletized_{HIGH}$	4.33 a	0.233 a
$Pelletized_{LOW}$	3.86 c	0.181 bc
$Pelletized_{MEDIUM}$	4.14 ab	0.187 bc
$Pelletized_{HIGH}$	4.32 a	0.200 b
p-value	<0.001	<0.001
F-test	***	***
CV (%)	2.15	5.30

*** $p \leq 0.001$. Low, medium, and high refer to application rates of unpelletized and pelletized cricket feces at 3.13, 6.25, and 12.5 Mg ha^{-1}. OC: organic C; TN: total N. Means that followed by the same letters in the same column indicate no statistically significant difference at $p \leq 0.05$ (Tukey's HSD test).

Table 3. Soil physicochemical properties as influenced by unpelletized and pelletized cricket feces in the plant bioassay experiment

Amendment	BD	pH	EC	CEC	OC	TN	NH_4^+-N	NO_3^--N	P	K	Ca	Mg	Na	Al	FDA	EA
	Mg m^{-3}		mS cm^{-1}	$cmol_c$ kg^{-1}	g kg^{-1}		mg kg^{-1}									me 100 g^{-1}
Unamended	1.58 bc	4.05 d	0.120 d	2.19 d	3.41 c	0.120 c	3.17 bc	1.36	25.7 e	16.8 c	203 d	19.6 e	10.2 d	14.15 a	334 c	0.173 a
$Unpelletized_{LOW}$	1.55 c	4.37 c	0.131 d	2.32 cd	3.56 bc	0.115 c	3.78 ab	1.52	38.6 d	19.4 c	231 cd	29.1 de	14.2 c	8.56 c	431 ab	0.095 b
$Unpelletized_{MEDIUM}$	1.54 c	4.58 bc	0.132 d	2.79 b	3.59 bc	0.147 b	3.10 bc	1.55	52.2 bc	31.5 c	328 b	34.2 cd	15.1 c	6.33 de	434 ab	0.018 d
$Unpelletized_{HIGH}$	1.63 a	5.09 a	0.199 ab	2.84 b	3.82 ab	0.159 b	2.52 c	1.52	81.5 a	63.0 b	385 a	49.6 ab	18.4 b	4.49 e	490 a	0.003 d
$Pelletized_{LOW}$	1.60 ab	4.39 c	0.141 cd	2.44 c	3.38 c	0.124 c	4.63 a	1.89	43.3 cd	32.7 c	240 c	30.0 d	16.4 bc	12.07 b	351 c	0.093 b
$Pelletized_{MEDIUM}$	1.58 a-c	4.70 b	0.170 bc	2.52 c	3.54 c	0.155 b	2.86 bc	1.71	63.3 b	57.7 b	344 b	40.6 bc	24.1 a	7.80 cd	414 b	0.053 c
$Pelletized_{HIGH}$	1.58 a-c	4.97 a	0.222 a	3.82 a	3.86 a	0.190 a	2.59 c	1.47	87.4 a	95.2 a	381 a	53.2 a	26.9 a	6.20 de	456 ab	0.044 c
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.222	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
F-test	***	***	***	***	***	***	*	ns	***	***	***	***	***	***	***	***
CV (%)	1.12	2.02	7.43	2.96	2.66	3.73	20.04	15.17	7.58	17.22	4.21	9.67	6.03	8.27	5.41	12.27

* p≤0.05; *** p≤0.001; ns: not significant. Low, medium, and high refer to application rates of unpelletized and pelletized cricket feces at 3.13, 6.25, and 12.5 Mg ha^{-1}. BD: bulk density; EC: electrical conductivity; CEC: cation exchange capacity; OC: organic C; TN: total N; EA: exchangeable acidity; FDA: fluorescein release. Means that are followed by the same letters in the same column indicate no statistically significant difference at p≤0.05 (Tukey's HSD test).

Table 4. Elemental contents in Chinese kale's shoot tissue as influenced by unpelletized and pelletized cricket feces in the plant bioassay experiment

Amendment	N	P	K	Ca	Mg	Na
	g kg^{-1}					
Unamended	12.8 c ‡	0.7 c	15.5 c	27.5 a	3.96 a	0.30 b
$Unpelletized_{LOW}$	13.9 c	8.0 b	17.2 c	18.7 b	2.32 b	0.54 b
$Unpelletized_{MEDIUM}$	17.1 ab	10.7 ab	17.4 c	17.2 bc	2.98 b	0.66 b
$Unpelletized_{HIGH}$	19.7 a	12.5 a	21.0 b	16.3 bc	2.80 b	2.70 a
$Pelletized_{LOW}$	13.3 c	9.8 ab	21.9 ab	11.7 c	2.64 b	0.74 b
$Pelletized_{MEDIUM}$	14.4 bc	12.2 a	20.6 b	13.2 bc	2.88 b	0.73 b
$Pelletized_{HIGH}$	18.8 a	11.9 a	24.0 a	13.0 bc	4.10 a	2.85 a
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
F-test	***	***	***	***	***	***
CV (%)	6.34	12.85	4.39	12.9	10.37	15.31

*** p≤0.001. Low, medium, and high refer to application rates of unpelletized and pelletized cricket feces at 3.13, 6.25, and 12.5 Mg ha^{-1}. Means that are followed by the same letters in the same column indicate no statistically significant difference at p≤0.05 (Tukey's HSD test).

Chinese kale biomass (Table 6), which included shoot fresh and dry weights, root dry weight, and total dry weight, was highest at the medium rate and decreased at the high rate compared to its lower rate for unpelletized feces. Treatments with pelletized feces resulted in significantly lower biomasses than their unpelletized counterparts, except for their high rates under root dry weight.

Nutrient uptake in kale shoots demonstrated that pelletized cricket feces resulted in consistently lower nutrient availability compared to unpelletized feces across all application rates (Table 7), with reduced N (36.2–69.5 *vs*. 69.7–105.7 mg $plant^{-1}$), P (26.7-48.5 *vs*. 35.9-79.4 mg $plant^{-1}$), K (59.1-97.7 *vs*. 77.9-132.0 mg $plant^{-1}$), Ca (31.5-53.1 *vs*. 82.3-127.5 mg $plant^{-1}$), Mg (7.1-16.7 *vs*. 10.5-22.0 mg $plant^{-1}$), and Na (2.0-11.6 *vs*. 2.4-17.0 mg $plant^{-1}$). Both pelletized and unpelletized cricket feces significantly improved N, P, K, and Na uptakes compared to unamended soil.

Table 5. Selected tissue nutrient ratios as influenced by unpelletized and pelletized cricket feces in the plant bioassay experiment

Amendment	K/Ca	K/Mg	Ca/Mg
Unamended	0.57 d	3.92 c	6.92 ab
$Unpelletized_{LOW}$	0.95 cd	7.44 a	7.85 a
$Unpelletized_{MEDIUM}$	1.01 c	5.84 b	5.80 bc
$Unpelletized_{HIGH}$	1.30 bc	7.53 a	5.82 bc
$Pelletized_{LOW}$	1.88 a	8.32 a	4.46 cd
$Pelletized_{MEDIUM}$	1.57 ab	7.13 ab	4.58 cd
$Pelletized_{HIGH}$	1.85 a	5.96 b	3.20 d
p-value	<0.001	<0.001	<0.001
F-test	***	***	***
CV (%)	10.59	7.14	10.01

*** p≤0.001. Low, medium, and high refer to application rates of unpelletized and pelletized cricket feces at 3.13, 6.25, and 12.5 Mg ha^{-1}. Ratios of these elements are expressed in g kg^{-1}. Means that are followed by the same letters in the same column indicate no statistically significant difference at p≤0.05 (Tukey's HSD test).

Cricket feces, unpelletized and pelletized, increased CROSS compared to unamended soil (0.092) (Table 8). Unpelletized treatments had CROSS values of 0.111, 0.117, and 0.163, while pelletized treatments showed higher values of 0.144, 0.192, and 0.244 for low, medium, and high rates, respectively.

DISCUSSION

Soil N transformation as affected by pelleted cricket feces amendment

The results of soil N parameters—NH_4^+-N (Figures 1a *vs.* 1b), NO_3^--N (Figures 1c *vs.* 1d), and net N mineralization rates (Figures 1e *vs.* 1f) — from the microcosm experiment identified the temporal changes in soil N status into two phases. The early phase (days 1-30) exhibited large N fluctuations, while the later phase (days 30 onwards) demonstrated relative N stability. The finding was consistent with Autaiwat and Butnan (2024), who demonstrated that the *r*-strategist microorganisms dominated the early phase of soil N transformation, while the later phase was dominated by the *K*-strategist. *R*-strategists are microorganisms that thrive in optimal environments but struggle in adverse conditions. This corresponds with the current study (Figure 2), where microbial activity highly fluctuated during the early phase. In the later phase, soil N status stabilized, consistent with the characteristics of *K*-strategists, which grow slowly but can endure harsh environments.

Pelletizing cricket feces decreased soil N mineralization rates (Figures 1e *vs*. 1f), leading to lower soil concentrations of NH_4^+-N (Figures 1a *vs*. 1b) and NO_3^--N (Figures 1c *vs*. 1d). The decreases in N mineralization could be attributed to the larger sizes of the feces, which limited the specific surface area and access for microorganisms, as seen in lower microbial activity, indicated by the fluorescein release, in the pelletized feces treatments (Figures 2a *vs*. 2b). In addition, it might be the fact that the pelletized feces decreased the release of soluble organic compounds, which served as a C source for N-mineralising microorganisms (Hadas et al., 1983).

The rises in soil NH_4^+-N (Figures 1a and 1b) and NO_3^--N concentrations (Figures 1c and 1d), and net N mineralization rates (Figures 1e and 1f) at higher application rates of both types of cricket feces are consistent with the high N content of the feces as detailed in table 1, suggesting that the feces contributed to the soil N pool.

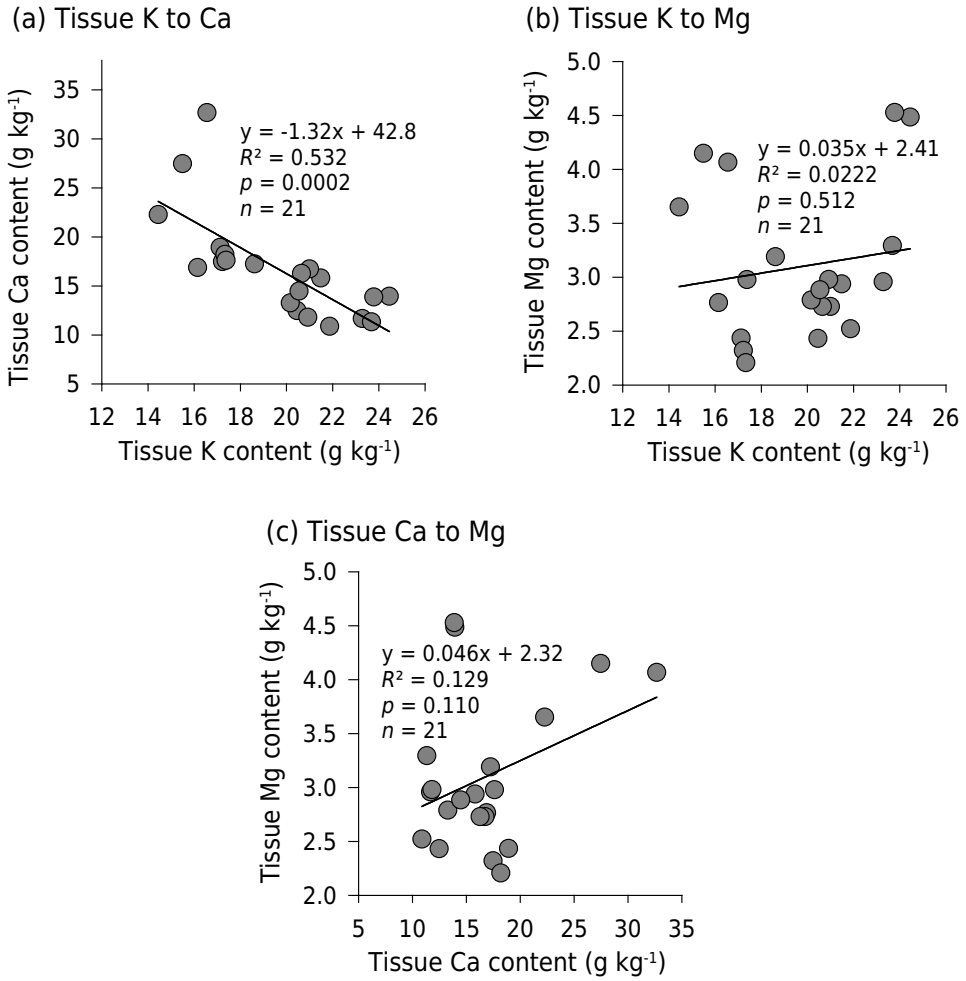

Figure 4. Regression analysis that illustrates the effect between tissue contents of cations: (a) K on Ca; (b) K on Mg; and Ca on Mg, in the plant bioassay experiment.

Table 6. Growth and shoot-root biomass of Chinese kale as influenced by unpelletized and pelletized cricket feces in the plant bioassay experiment

Amendment	Shoot FW	Shoot DW	Root DW	Total DW
	g plant^{-1}			
Unamended	11.8 f	1.91 e	0.43 d	2.34 d
Unpelletized$_{LOW}$	23.7 cd	4.52 c	0.77 b	5.29 c
Unpelletized$_{MEDIUM}$	39.3 a	7.40 a	1.10 a	8.50 a
Unpelletized$_{HIGH}$	34.3 b	6.27 b	0.83 b	7.10 b
Pelletized$_{LOW}$	15.4 e	2.71 de	0.57 cd	3.28 d
Pelletized$_{MEDIUM}$	22.1 d	3.64 cd	0.68 bc	4.31 c
Pelletized$_{HIGH}$	26.6 c	4.08 c	0.83 b	4.90 c
p-value	<0.001	<0.001	<0.001	<0.001
F-test	***	***	***	***
CV (%)	5.16	8.48	8.39	6.89

*** p≤0.001. Low, medium, and high refer to application rates of unpelletized and pelletized cricket feces at 3.13, 6.25, and 12.5 Mg ha^{-1}. FW: fresh weight; DW: dry weight. Means that are followed by the same letters in the same column indicate no statistically significant difference at p≤0.05 (Tukey's HSD test).

Table 7. Plant nutrient uptake as affected by varied application rates of unpelletized and pelletized cricket feces in the plant bioassay experiment

Amendment	N	P	K	Ca	Mg	Na
	mg plant^{-1}					
Unamended	30.0 d ‡	1.4 d	29.5 d	51.8 cd	7.5 c	0.6 d
Unpelletized$_{LOW}$	69.7 a-c	35.9 bc	77.9 bc	82.3 b	10.5 c	2.4 cd
Unpelletized$_{MEDIUM}$	105.7 a	79.4 a	128.7 a	127.5 a	22.0 a	4.9 c
Unpelletized$_{HIGH}$	99.6 ab	78.0 a	132.0 a	102.0 b	17.5 b	17.0 a
Pelletized$_{LOW}$	36.2 cd	26.7 c	59.1 c	31.5 d	7.1 c	2.0 cd
Pelletized$_{MEDIUM}$	67.4 bc	44.1 b	74.7 bc	47.9 cd	10.5 c	2.6 cd
Pelletized$_{HIGH}$	69.5 a-c	48.5 b	97.7 b	53.1 c	16.7 b	11.6 b
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
F-test	***	***	***	***	***	***
CV (%)	19.58	12.93	9.98	10.74	11.61	21.27

*** p≤0.001. Low, medium, and high refer to application rates of unpelletized and pelletized cricket feces at 3.13, 6.25, and 12.5 Mg ha^{-1}. Means that are followed by the same letters in the same column indicate no statistically significant difference at p≤0.05 (Tukey's HSD test).

Table 8. Cation ratio of soil structural stability (CROSS) as affected by varied application rates of unpelletized and pelletized cricket feces of the plant bioassay experiment

Amendment	CROSS
Unamended	0.092 e
Unpelletized$_{LOW}$	0.111 de
Unpelletized$_{MEDIUM}$	0.117 de
Unpelletized$_{HIGH}$	0.163 bc
Pelletized$_{LOW}$	0.144 cd
Pelletized$_{MEDIUM}$	0.192 b
Pelletized$_{HIGH}$	0.244 a
p-value	<0.001
F-test	***
CV (%)	9.59

*** p≤0.001. Low, medium, and high refer to application rates of unpelletized and pelletized cricket feces at 3.13, 6.25, and 12.5 Mg ha^{-1}. Means that are followed by the same letters in the same column indicate no statistically significant difference at p≤0.05 (Tukey's HSD test).

Soil N dynamics provided insights into the optimal timing for crop planting. The NH_4^+ and NO_3^- levels were considered to determine effective N use. The ratios of NH_4^+-N/NO_3^--N of both unpelletized (Figure 1g) and pelletized cricket feces (Figure 1h) indicated potential NH_4^+ toxicity, as ratios exceeding 1 were associated with NH_4^+ phytotoxicity (Wang et al., 2022). In the current study, these ratios were generally above 1 during the first 15 days, but fell below 1 afterward. Examining this alongside soil NH_4^+-N concentrations (Figures 1a and 1b), which peaked on day 5, underscored the risk of NH_4^+ phytotoxicity. Meanwhile, NO_3^--N peaked on day 15. To mitigate NH_4^+ toxicity, it was recommended that crops be planted after day 5, while to prevent NO_3^- deficiency, planting should occur before day 15. Therefore, the ideal planting window was identified as being between 5 and 15 days after the incorporation of the feces. In addition, it was noted on day 5 that the high rate of unpelletized cricket feces produced a NO_3^--N concentration of 8.54 mg kg^{-1} (11.84 mmol L^{-1} NO_3^-), which could potentially cause phytotoxicity (Ferrario-Méry et al., 2005).

Contrary to expectations, pelletized cricket feces did not delay soil N mineralization rates. Instead, unpelletized feces produced higher concentrations of soil NH_4^+-N (Figures 1a and 1b) and NO_3^--N (Figures 1c *vs*. 1d), and N mineralization rates (Figure 1e *vs*. 1f) throughout most of the incubation period, with no difference exhibited after day 30. To further explore soil N fate, it was illustrated that soil total N content at the end of the incubation lowered in the pelletized amended soils (Table 2). This prompted an inquiry about the fate of N from the pelletized feces. Where was soil N from the pelletized feces away? Nitrogen derived from animal manures is commonly lost through NH_3 volatilization (Hung et al., 2022); however, this was unlikely in this case, as pelletization theoretically mitigates such N depletion (Wester-Larsen et al., 2022) by decreasing the specific surface area and pH (Watson and Kilpatrick, 1991). It was illustrated in this study that the larger size of pelletized feces limited the release of NH_4^+ (Figures 1a *vs*. 1b), which is the precursor to volatilized NH_3, and also lowered the pH (Figures 3a *vs*. 3b). Therefore, it is most likely that N in the pelletized treatments was lost through gaseous N under anaerobic conditions. This aligns with a previous study by Cabrera et al. (1994), who found that pelletized poultry excrement led to increased N_2O emissions due to the anaerobic conditions within the pellets. However, there is an argument as to how N_2O was produced if the pellets are under anaerobic conditions. Specifically, while N_2O production via denitrification occurs in oxygen-deprived soil, it requires the conversion of NO_3^- to N_2O. This conversion depends on N_2O being available, which itself is produced through ammonification and nitrification — both of which require oxygen.

Nevertheless, the interior of the pellets might not be completely devoid of oxygen, allowing some degree of ammonification and nitrification to occur. This would enable the production of NH_4^+ and NO_3^- within the pellets, which are precursors for the denitrification. Additionally, N might be lost through another process that occurs in oxygen-deprived soil, particularly anaerobic ammonium oxidation, which transforms NH_4^+ directly into N_2 (Luther et al., 1997).

Interestingly, although the levels of soil N—specifically NH_4^+-N, NO_3^--N, and net N mineralization rates—increased during the early phase under the microcosm experiment, microbial activity sharply declined between days 5 and 10 (Figures 2a and 2b). The decline might have reflected a shift in the microbial community, as noted by Tang et al. (2024), who stated that microbial communities typically transition during N mineralization, with some microorganisms decreasing in abundance as new, more efficient groups emerge. Autaiwat and Butnan (2024) also described how *r*-strategist microorganisms initially dominated the early phase of N mineralization but subsequently declined as soil N levels decreased. Despite this reduction in initial microbial activity, organic compounds continued to decompose and release N (Alexander, 1991). Later, *K*-strategist microorganisms, which were more efficient yet exhibited lower activity, became the dominant group responsible for the later phase of soil N mineralization.

Acidity- and potential acidic-cation-derived phytotoxicity in soils with cricket feces amendments

Sandy soils employed in the current study had pH 4.10 and 4.64 (Table 1), which were classified as strongly acidic (Slattery et al., 1999). Although not as alkaline as cow manure (pH 8.3) (Tripetchkul et al., 2012) or chicken manure (pH 7.7) (Thepsilvisut et al., 2022), the cricket feces (pH 6.25-6.96) used in the current study could ameliorate soil acidity, as seen in the raised pH of the cricket feces amended soils (Figures 3a and 3b), because of the higher pH of the feces than the initial soils.

Animal manures commonly contain alkalis, e.g., $CaCO_3$ and $Ca(HCO_3)_2$, which function to raise soil pH (Rayne and Aula, 2020), and have organic anions, e.g., malate, citrate, and tartrate, that neutralize acidity and ameliorate the toxicity of acidic cations, i.e., Al, Fe, and Mn (Hue, 1992), which are commonly found in tropical soils (von Uexküll and Mutert, 1995). These organic molecules bind to acidic cations, e.g., Al, and act as reducing

agents, deactivating these ions and eventually alleviating their phytotoxic property in acidic soils (Hue et al., 2001). These mechanisms were likely exhibited in the cricket feces-derived acidic sandy soils employed in the current study.

The slightly lower soil pH in soils amended with pelletized cricket feces relative to the unpelletized counterparts (Figures 3a *vs*. 3b) might be attributed to decreases in releasing alkalis and organic molecules from the pellets (Hadas et al., 1983). Furthermore, the pH declines recorded between days 5 and 15 (Figures 3a *vs*. 3b) coincided with increases in NO_3^- concentrations (Figures 1c *vs*. 1d), demonstrating their high nitrification rates releasing H^+ ions, which further lower soil pH (Weil and Brady, 2017).

Improved and depressed plant yield as affected by pelletized feces amendment

The improved kale biomass with increasing application rates of pelletized feces (Table 6) could be attributed to the properties of nutrient-rich sources and soil acidity amelioration. However, pelletized feces resulted in lower kale biomass in comparison to the same rates of unpelletized counterparts. These reductions in kale biomass were due to (i) lower nutrient availability and (ii) less effective soil acidity alleviation. Specifically, pelletized cricket feces reduced soil NO_3^- levels, as seen in consistently lower NO_3^--N concentrations compared to unpelletized feces throughout the microcosm study (Figures 1c *vs*. 1d). This decreased N availability commonly deteriorates plant growth, particularly vegetables, which utilised NO_3^- more effectively than NH_4^+, even though they could take up N in both forms (Mengel and Kirkby, 2001).

In the plant bioassay, the nutrient levels in the soil (Table 3) and shoot tissue (Table 4) were not consistent with the kale biomass (Table 6) when comparing unpelletized versus pelletized cricket feces. Soil properties measured at kale harvest (Table 3), indicate that nutrients had been taken up from the soil. Meanwhile, the unclear kale biomass responses (Table 6) to tissue nutrient contents (Table 4) might be attributed to the dilution effect, where plants with larger biomass contain lower nutrient concentrations (Mengel and Kirkby, 2001). To further investigation, nevertheless, the yields were consistent with nutrient uptakes in kale shoots (Table 7), demonstrating that pelletized cricket feces produced lower uptakes of N, P, K, Ca, Mg, and Na compared to their unpelletized counterparts.

Pelletized cricket feces were less effective at ameliorating soil Al concentrations and exchangeable acidity, as seen in the plant bioassay experiment (Table 3), which also illustrated consistent responses in soil pH in the microcosm experiment (Figures 3a *vs*. 3b). The decreased effectiveness of the pelletized feces in improving nutrient availability and alleviating soil acidity was possibly due to their lower solubility (Hadas et al., 1983).

Although pelletized cricket feces brought about less soil fertility and depressed kale biomass, the crop was short-lived. The potential of pelletized feces to be more beneficial in the longer term warrants further investigation.

K and NO_3^- phytotoxicity rendered by the high rates of unpelletized cricket feces

Suppressed kale biomass in response to the high rate of the unpelletized feces (Table 6) was manifested by K antagonistic to Ca, as supported by the significant negative effect of tissue K on Ca (Figure 4a). At this application rate of unpelletized feces, tissue K content reached 21 g kg^{-1} (Table 4), which is classified as high for *Brassica* spp. with a threshold of 19 g kg^{-1} (Reuter et al., 1997). On the contrary, tissue Ca content was as low as 16.3 g kg^{-1}, below the deficiency level of 20 g kg^{-1} (Reuter et al., 1997). Moreover, the depressed kale biomass was diagnosed as NO_3^- phytotoxicity, supported by the high soil NO_3^- concentrations on day 15 (Figure 1c), coinciding with the transplanting date, which reached 8.54 mg kg^{-1} equivalent to 11.8 mmol L^{-1} of NO_3^-, exceeding the toxic level for plants of 7.24 mg kg^{-1} of NO_3^- or 10 mmol L^{-1} of NO_3^- (Ferrario-Méry et al., 2005).

High Na derived from cricket feces influencing soil and kale

Even though the results of the current study demonstrated that cricket feces of both types possessed high Na content — specifically, unpelletized feces at 1007 mg kg^{-1} in the microcosm and 1825 mg kg^{-1} in the bioassay, and pelletized feces at 1126 and 1654 mg kg^{-1}, respectively (Table 1) — their EC indicated potential soil saline phytotoxicity. The EC for unpelletized feces was 12.5 and 12.3 mS cm^{-1}, while pelletized feces recorded 12.3 and 19.1 mS cm^{-1}, respectively. Meanwhile, the resulting Na concentrations after the application of cricket feces were only 14.2 to 26.9 mg kg^{-1} equivalent to 0.89 to 1.69 mmol L^{-1} Na, with EC ranging from 0.131 to 0.222 mS cm^{-1}. These soil Na and EC levels resulting from the effects of cricket feces-derived Na remained below the phytotoxic threshold of 10 mmol L^{-1} (Tayebi-Meigooni et al., 2014) and 0.39 mS cm^{-1} (Salachna et al., 2017). However, the long-term effect of high Na from the application of cricket feces requires further evaluation.

Soil structural degradation: the adverse effect of cricket feces amendment

Although in the current study, cricket feces had low density—0.43 Mg m^{-3} for unpelletized and 0.28 Mg m^{-3} for pelletized—compared to the initial soil bulk density of 1.44 Mg m^{-3} (Table 1). Consequent to amending the soil, both types of cricket feces increased soil bulk density (Table 3), in particular the high rate of unpelletized feces, which resulted in a bulk density of 1.63 Mg m^{-3}, exceeding the satisfactory range of 1.40 to 1.60 Mg m^{-3} for coarsely textured soils (Hazelton and Murphy, 2007). These increases in soil bulk density might be attributed to the degradation of soil structure rendered by clay dispersion as described by Goldberg et al. (2020).

The increase in soil bulk density observed with higher rates of unpelletized cricket feces was due to the dispersion of soil particles. The dispersion phenomenon was supported by the higher CROSS values in soils amended with unpelletized feces compared to those with pelletized counterparts, as well as the increasing CROSS values with higher rates of pelletized feces (Table 8). The CROSS reflected clay dispersion, which is the activity of Na and K (Rengasamy and Marchuk, 2011). In this study, it was noted that the levels of these two monovalent cations, *viz* Na and K, increased with higher application rates (Table 3). However, the negative effect of the clay dispersion observed in the current study might only be short-term. Animal manures generally provide long-term benefits by acting as cementing agents in aggregate formation, bringing about a decrease in soil bulk density (Scotti et al., 2015).

CONCLUSIONS

Pelletized cricket feces decreased soil N mineralization, leading to lower concentrations of soil NH_4^+ and NO_3^-, reduced nutrient availability, and lower potential to decrease acidity. Its consequent ability to promote kale biomass was suppressed. Unpelletized cricket feces were more effective in enhancing soil fertility and kale yield. Nevertheless, caution was advised when applying them at a high rate of 12.5 Mg ha^{-1}, especially in sandy soils with low nutrient retention. This excessive application rate depressed kale biomass with the K antagonistic effects on Ca and NO_3^- toxicity.

DATA AVAILABILITY

The data that support this study will be shared upon reasonable request to the corresponding author.

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AUTHOR CONTRIBUTIONS

Conceptualization: Somchai Butnan (lead).

Data curation: Jenjira Kotama (equal), Somchai Butnan (supporting) and Theerapat Chumpla (equal).

Formal analysis: Jenjira Kotama (equal), Somchai Butnan (supporting) and Theerapat Chumpla (equal).

Funding acquisition: Somchai Butnan (lead).

Investigation: Jenjira Kotama (equal) and Theerapat Chumpla (equal).

Methodology: Jenjira Kotama (equal), Somchai Butnan (supporting) and Theerapat Chumpla (equal).

Project administration: Somchai Butnan (lead).

Supervision: Somchai Butnan (lead).

Validation: Somchai Butnan (lead).

Visualization: Jenjira Kotama (equal), Somchai Butnan (supporting) and Theerapat Chumpla (equal).

Writing – original draft: Somchai Butnan (lead).

Writing – review & editing: Jenjira Kotama (equal), Somchai Butnan (lead) and Theerapat Chumpla (equal).

REFERENCES

Adeli A, McCarty JC, Read JJ, Willers JL, Feng G, Jenkins JN. Subsurface band placement of pelletized poultry litter in cotton. Agron J. 2016;108:1356-66. https://doi.org/10.2134/agronj2015.0373

Adeli A, Read JJ, McCarty J, Jenkins JN, Feng G. Soybean yield and nutrient utilization following long-term pelletized broiler litter application to cotton. Agron J. 2015;107:1128-34. https://doi.org/10.2134/agronj14.0497

Adeli A, Tewolde H, Jenkins JN. Broiler litter type and placement effects on corn growth, nitrogen utilization, and residual soil nitrate-nitrogen in a no-till field. Agron J. 2012;104:43-8. https://doi.org/10.2134/agronj2011.0093

Alexander M. Introduction to soil microbiology. Florida: Krieger Publishing Company; 1991.

Autaiwat S, Butnan S. Nitrogen transformation for varying application rates of incorporated and surfaced placements of cricket feces in a tropical sandy soil. Trop Agric. 2024;101:497-509.

Butnan S. Application rates of cricket feces influencing soil properties and rice yield in soils of different moisture contents. Indian J Agric Res. 2024;58:279-84. https://doi.org/10.18805/IJARe.AF-803

Cabrera ML, Chiang SC, Merka WC, Pancorbo OC, Thompson SA. Pelletizing and soil water effects on gaseous emissions from surface-applied poultry litter. Soil Sci Soc Am J. 1994;58:807-11. https://doi.org/10.2136/sssaj1994.03615995005800030024x

Ferrario-Méry S, Bouvet M, Leleu O, Savino G, Hodges M, Meyer C. Physiological characterisation of Arabidopsis mutants affected in the expression of the putative regulatory protein PII. Planta. 2005;223:28-39. https://doi.org/10.1007/s00425-005-0063-5

Fujii K, Hayakawa C, Panitkasate T, Maskhao I, Funakawa S, Kosaki T, Nawata E. Acidification and buffering mechanisms of tropical sandy soil in northeast Thailand. Soil Till Res. 2017;165:80-7. https://doi.org/10.1016/j.still.2016.07.008

Goldberg N, Nachshon U, Argaman E, Ben-Hur M. Short term effects of livestock manures on soil structure stability, runoff and soil erosion in semi-arid soils under simulated rainfall. Geosciences. 2020;10:213. https://doi.org/10.3390/geosciences10060213

Golden BR, Slaton NA, Norman RJ, Gbur Jr EE, Brye KR, DeLong RE. Recovery of nitrogen in fresh and pelletized poultry litter by rice. Soil Sci Soc Am J. 2006;70:1359-69. https://doi.org/10.2136/sssaj2005.0298

Green VS, Stott DE, Diack M. Assay for fluorescein diacetate hydrolytic activity: Optimization for soil samples. Soil Biol Biochem. 2006;38:693-701. https://doi.org/10.1016/j.soilbio.2005.06.020

Hadas A, Bar-Yosef B, Davidov S, Sofer M. Effect of pelleting, temperature, and soil type on mineral nitrogen release from poultry and dairy manures. Soil Sci Soc Am J. 1983;47:1129-33. https://doi.org/10.2136/sssaj1983.03615995004700060014x

Halloran A, Hanboonsong Y, Roos N, Bruun S. Life cycle assessment of cricket farming in north-eastern Thailand. J Clean Prod. 2017;156:83-94. https://doi.org/10.1016/j.jclepro.2017.04.017

Hazelton P, Murphy B. Interpreting soil test results: What do all the numbers mean? Collingwood: CSIRO Publising; 2007.

Horneck DA, Miller R. Determination of total nitrogen in plant tissue. In: Kalra YP, editor. Handbook of reference methods for plant analysis. Boca Raton: CRC Press; 1998. p. 75-83.

Hue NV. Correcting soil acidity of a highly weathered Ultisol with chicken manure and sewage sludge. Commun Soil Sci Plant Anal. 1992;23:241-64. https://doi.org/10.1080/00103629209368586

Hue NV, Vega S, Silva JA. Manganese toxicity in a Hawaiian Oxisol affected by soil pH and organic amendments. Soil Sci Soc Am J. 2001;65:153-60. https://doi.org/10.2136/sssaj2001.651153x

Hung CY, Hussain N, Husk BR, Whalen JK. Ammonia volatilization from manure mixed with biochar. Can J Soil Sci. 2022;102:177-86. https://doi.org/10.1139/cjss-2021-0029

Jones JB. Laboratory guide for conducting soil tests and plant analysis. Boca Raton: CRC Press; 2001.

Kemsawasd V, Inthachat W, Suttisansanee U, Temviriyanukul P. Road to the red carpet of edible crickets through integration into the human food chain with biofunctions and sustainability: A review. Int J Mol Sci. 2022;23:1801. https://doi.org/10.3390/ijms23031801

Kroetsch D, Wang C. Particle size distribution. In: Carter MR, Gregorich EG, editors. Soil sampling and methods of analysis. 2nd ed. Oxford: CRC Press; 2008. p. 713-25.

Luther GW, Sundby B, Lewis BL, Brendel PJ, Silverberg N. Interactions of manganese with the nitrogen cycle: Alternative pathways to dinitrogen. Geochim Cosmochim Acta. 1997;61:4043-52. https://doi.org/10.1016/S0016-7037(97)00239-1

Lynch DH, Zheng Z, Zebarth BJ, Martin RC. Organic amendment effects on tuber yield, plant N uptake and soil mineral N under organic potato production. Renew Agr Food Syst. 2008;23:250-9. https://doi.org/10.1017/S1742170508002330

Matisic M, Dugan I, Bogunovic I. Challenges in sustainable agriculture—The role of organic amendments. Agriculture. 2024;14:643. https://doi.org/10.3390/agriculture14040643

Mehmood I, Bari A, Irshad S, Khalid F, Liaqat S, Anjum H, Fahad S. Carbon cycle in response to global warming. In: Fahad S, Hasanuzzaman M, Alam M, Ullah H, Saeed M, Ali Khan I, Adnan M, editors. Environment, climate, plant and vegetation growth. Cham: Springer International Publishing; 2020. p. 1-15.

Mengel K, Kirkby EA. Principles of plant nutrition. Dordrecht: Kluwer Academic Publishers; 2001.

Miller RO. Nitric-perchloric acid wet digestion in an open vessel. In: Kalra YP, editor. Handbook of reference methods for plant analysis. Boca Raton: CRC Press; 1988. p. 57-61.

Ndegwa PM, Thompson SA, Merka WC. Fractionation of poultry litter for enhanced utilization. T ASAE. 1991;34:992-7. https://doi.org/10.13031/2013.31761

Nelson DW, Sommers LE. Total carbon, organic carbon, and organic matter. In: Spark DL, editor. Methods of soil analysis Part 2 Chemical and microbiological propterties. Madison, Wisconsin: SSSA; 1982. p. 539-79.

Pampuro N, Bertora C, Sacco D, Dinuccio E, Grignani C, Balsari P, Cavallo E, Vernal MP. Fertilizer value and greenhouse gas emissions from solid fraction pig slurry compost pellets. J Agric Sci. 2017;155:1646-58. https://doi.org/10.1017/S002185961700079X

Pansu M, Gautheyrou J. Handbook of soil analysis: Mineralogical, organic and inorganic methods. Heidelberg: Springer Verlag; 2006.

Rayne N, Aula L. Livestock manure and the impacts on soil health: A review. Soil Syst. 2020;4:64. https://doi.org/10.3390/soilsystems4040064

Rengasamy P, Marchuk A. Cation ratio of soil structural stability (CROSS). Soil Res. 2011;49:280-5. https://doi.org/10.1071/SR10105

Reuter DJ, Edwards DG, Wilhelm NS. Temperate and tropical crops. In: Reuter D, Robinson JB, editors. Plant analysis: An interpretation manual. Collingwood: CSIRO Publishing; 1997. p. 83-284.

Reza-Bagheri A-AG, Hossein-Kianmehr M, Sarvastani Z, Hamzekhanlu M. The effect of pellet fertilizer application on corn yield and its components. Afr J Agric Res. 2011;6:2364-71. https://doi.org/10.5897/AJAR11.011

Sahin O, Taskin MB, Kadioglu YK, Inal A, Pilbeam DJ, Gunes A. Elemental composition of pepper plants fertilized with pelletized poultry manure. J Plant Nutr. 2014;37:458-68. https://doi.org/10.1080/01904167.2013.864307

Salachna P, Piechocki R, Byczyńska A. Plant growth of curly kale under salinity stress. J Ecol Eng. 2017;18:119-24. https://doi.org/10.12911/22998993/66247

Samac DA, Tesfaye M. Plant improvement for tolerance to aluminum in acid soils – A review. Plant Cell Tissue Organ Cult. 2003;75:189-207. https://doi.org/10.1023/A:1025843829545

Scotti R, Bonanomi G, Scelza R, Zoina A, Rao MA. Organic amendments as sustainable tool to recovery fertility in intensive agricultural systems. J Soil Sci Plant Nutr. 2015;15:333-52. https://doi.org/10.4067/S0718-95162015005000031

Slattery WJ, Conyers MK, Aitken RL. Soil pH, alumunium, manganese and lime requirement. In: Peverill KI, Sparrow LA, Reuter DJ, editors. Soil analysis: An interpretation manual. Collingwood, Autralia: CSIRO Publishing; 1999. p. 103-28.

Stevenson FJ. Nitrogen — Inorganic forms. In: Spark DL, editor. Methods of soil analysis Part 2 Chemical and microbiological propterties. Madison, Wisconsin: SSSA; 1982. p. 643-98.

Suppadit T, Poungsuk P. Utilization of broiler litter pellets to substitute mixed feed pellets in fattening steers. J ISSAAS. 2010;16:55-67.

Tang H, Liu Y, Yang X, Huang G, Liang X, Shah AN, Nawaz M, Hassan MU, Qumsani AT, Qari SH. Multiple cropping effectively increases soil bacterial diversity, community abundance and soil fertility of paddy fields. BMC Plant Biol. 2024;24:715. https://doi.org/10.1186/s12870-024-05386-w

Tayebi-Meigooni A, Awang Y, Biggs AR, Mohamad R, Madani B, Ghasemzadeh A. Mitigation of salt-induced oxidative damage in Chinese kale (*Brassica alboglabra* L.) using ascorbic acid. Acta Agr Scand Sect B. 2014;64:13-23. https://doi.org/10.1080/09064710.2013.869347

Thepsilvisut O, Chutimanukul P, Sae-Tan S, Ehara H. Effect of chicken manure and chemical fertilizer on the yield and qualities of white mugwort at dissimilar harvesting times. PLoS One. 2022;17:e0266190. https://doi.org/10.1371/journal.pone.0266190

Thomas BW, Li X, Nelson V, Hao X. Anaerobically digested cattle manure supplied more nitrogen with less phosphorus accumulation than undigested manure. Agron J. 2017;109:836-44. https://doi.org/10.2134/agronj2016.12.0719

Tripetchkul S, Pundee K, Koonsrisuk S, Akeprathumchai S. Co-composting of coir pith and cow manure: initial C/N ratio vs physico-chemical changes. Int J Recycl Org Waste Agricult. 2012;1:15. https://doi.org/10.1186/2251-7715-1-15

Vityakon P. Degradation and restoration of sandy soils under different agricultural land uses in northeast Thailand: A review. Land Degrad Dev. 2007;18:567-77. https://doi.org/10.1002/ldr.798

von Uexküll HR, Mutert E. Global extent, development and economic impact of acid soils. Plant Soil. 1995;171:1-15. https://doi.org/10.1007/BF00009558

Wang Y, Zhang X, Liu H, Sun G, Song S, Chen R. High NH_4^+/NO_3^- ratio inhibits the growth and nitrogen uptake of Chinese kale at the late growth stage by ammonia toxicity. Horticulturae. 2022;8:8. https://doi.org/10.3390/horticulturae8010008

Watson CJ, Kilpatrick DJ. The effect of urea pellet size and rate of application on ammonia volatilization and soil nitrogen dynamics. Fert Res. 1991;28:163-72. https://doi.org/10.1007/BF01049746

Weil RR, Brady NC. The nature and properties of soils. New York: Pearson Education; 2017.

Wester-Larsen L, Müller-Stöver DS, Salo T, Jensen LS. Potential ammonia volatilization from 39 different novel biobased fertilizers on the European market – A laboratory study using 5 European soils. J Environ Manage. 2022;323:116249. https://doi.org/10.1016/j.jenvman.2022.116249

Wild PL, Van Kessel C, Lundberg J, Linquist BA. Nitrogen availability from poultry litter and pelletized organic amendments for organic rice production. Agron J. 2011;103:1284-91. https://doi.org/10.2134/agronj2011.0005

Yang X, Li G, Jia X, Zhao X, Lin Q. Net nitrogen mineralization delay due to microbial regulation following the addition of granular organic fertilizer. Geoderma. 2020;359:113994. https://doi.org/10.1016/j.geoderma.2019.113994

Yost JL, Hartemink AE. Soil organic carbon in sandy soils: A review. Adv Agron. 2019;158:217-310. https://doi.org/10.1016/bs.agron.2019.07.004

Zafari A, Kianmehr MH. Management and reduction of chemical nitrogen consumption in agriculture. Am J Plant Sci. 2012;3:1827-34. https://doi.org/10.4236/ajps.2012.312A224

Zebarth B, Chabot R, Coulombe J, Simard R, Douheret J, Tremblay N. Pelletized organo-mineral fertilizer product as a nitrogen source for potato production. Can J Soil Sci. 2005;85:387-95. https://doi.org/10.4141/S04-071