



Research article

Nutrient composition of diverse organic residues and their long-term effects on available nutrients in a tropical sandy soil

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ARTICLE INFO

Keywords:

Long-term experiment
 Nutrient composition
 Organic residue
 Available nutrient
 Tropical sandy soil
 Chemistry
 Food science
 Agricultural science
 Environmental science
 Earth sciences

ABSTRACT

Intensive use of sandy soils for agriculture leads to significant land degradation. The application of locally available organic residues can improve soil fertility, particularly in the context of organic farming practices. This research examined nutrient concentrations in locally available organic residues with different biochemical compositions/qualities and investigated the effects of long-term application of these residues on available nutrients, such as P, K, Ca, Mg, Fe, Mn, and Zn, as well as on total organic carbon (TOC) accumulation in tropical sandy soil. A field experiment was conducted in Northeast Thailand, where four local organic residues, groundnut stover (GN), tamarind leaf litter (TM), dipterocarp leaf litter (DP), and rice straw (RS), had been applied annually for 22 years. These organic residues were acidic (pH 3.7–5.8). The macronutrients N, P, and K were present at elevated levels in the high-quality organic residue GN, whereas medium-quality TM and low-quality RS and DP were dominated by the macronutrients Ca and Mg and the micronutrients Fe, Mn, and Zn. The incorporation of organic residues, particularly TM, resulted in the accumulation of TOC. Furthermore, long-term incorporation of TM increased soil pH, whereas incorporation of GN, DP, and RS did not. The higher increase in the soil pH of TM soil is likely because TM contains higher levels of ash alkalinity compared to other residues. The application of medium-quality TM increased the soil available P, Ca, and Mg, whereas low-quality organic residue RS and DP applications increased the concentrations of soil micronutrients (e.g., Mn and Zn). However, long-term applications of local organic residues did not increase available K in the sandy soil.

1. Introduction

Sandy soils are infertile due to their high sand content (>85%), which contributes to their low water holding capacity, soil pH (4.5–5.5), cation exchange capacity, soil organic matter, and plant nutrients, ultimately leading to low crop productivity (Fujii et al., 2017). To raise the level of plant nutrients and crop productivity in these soils, both mineral and organic fertilizers are used to ensure sustainability of the food production system (Cai et al., 2019). At present, organic farming, which precludes the use of mineral fertilizers, synthetic pesticides, and genetically modified crops, is sought after (Nielsen, 2019). It is undeniable that this is a trend in today's agricultural world, as seen by a yearly increase of 20–25% in the market for organic foods (Ramesh et al., 2005). Farmers prefer using manures, green manures, composts, and plant residues as alternative sources of plant nutrients and amendments for improving the

physicochemical properties of sandy soils (e.g., Vityakon et al., 2000; Ksawery et al., 2010; Cai et al., 2019; Li et al., 2019). Livestock manures are effective in increasing soil fertility by increasing soil organic carbon, nutrients, and soil pH, which positively affect crop yields (Nielsen, 2019). However, manures are scarce in small farming systems in Northeast Thailand due to the reduced number of livestock on farms, as mechanization in farm operations has been increasing (Rambo, 2017). Organic materials and fertilizers need to be brought in from other regions of Thailand; however, transport costs add to the expense of practicing organic farming. Locally available organic residues and local agricultural wastes are increasingly valuable for their use in sustaining soil fertility.

Applications of organic residues to soils have been shown to increase soil fertility in general, including increasing soil aggregation, soil organic carbon, soil pH, and soil nutrients. In addition, the application of organic materials to soils decreases the mobilization of potentially toxic elements

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Received 9 June 2020; Received in revised form 16 October 2020; Accepted 20 November 2020

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(e.g., Al, As, heavy metals, and rare-earth elements) (Samahadthai et al., 2010; Li et al., 2019; Yusiharni and Gilkes, 2012; Sukitprapanon et al., 2019). Plant residues contain variable levels of nutrients depending on plant species, plant part, and plant age (Palm et al., 2001; Vityakon, 2001; Yusiharni and Gilkes, 2012). Li et al. (2019) reported that the average, total element concentrations in biochars derived from crop residues, including rice husks, corn stover, sugarcane residue, and corn cobs, were Si (7.1%), K (2.7%), N (1.2%), Ca (1.2%), Mg (0.54%), P (0.32%), and S (0.56%). Furthermore, Prakongkep et al. (2015) showed that the total element concentrations of agricultural waste biochars, including soybean cake, eucalyptus wood, durian shell, and oil palm fruit, were as high as 0.93% for P, 5.1% for K, 4.3% for Ca, and 0.82% for Mg. Plant residues are, therefore, recognized as multinutrient amendments.

In Thailand, sandy soils occupy an area of approximately 18811 km², of which 13656 km² are in the northeast (Land Development Department, 2015). The undulating terrain in the northeast used to be covered by dry dipterocarp forests, which enabled a closed nutrient cycling system (Vityakon, 2001). However, when the forest was gradually cleared to establish agriculture, especially upland crops (e.g., sugarcane and cassava), since the 1960s, nutrient cycling became an open system resulting in a further decrease in soil fertility (Vityakon, 2001). Farmers in Northeast Thailand appreciate the soil amendment values of organic residues and have been using various types of local organic residues, such as rice straw, green manures, and tree leaf litter, for such purposes (Vityakon et al., 2000). It is established that mineralization of organic residues and release of plant nutrients are mostly controlled by their biochemical composition, such as N, the C/N ratio, lignin, and polyphenols (Palm et al., 2001).

Previous studies on the long-term, continuous incorporation of organic residues of contrasting quality in sandy soils in Thailand revealed that such a practice influenced the accumulation of soil organic carbon (SOC), locations of SOC stored in the soil matrix (i.e., soil aggregates and silt + clay fractions (Samahadthai et al., 2010; Puttaso et al., 2013)), and release of mineral N (Vityakon et al., 2000). In addition, Kunlanit et al. (2014) reported that mineralization of organic residues is controlled not only by N, the C/N ratio, lignin, and polyphenols but also by cellulose. However, knowledge of the concentrations of plant nutrients in local organic residues and their long-term effects on plant-nutrient availability in sandy soils is limited. This study aims to determine (1) the contents of plant-nutrient elements in local organic residues and (2) the long-term application effects (>22 years) of local organic residues with contrasting quality on plant-available nutrients, such as P, K, Ca, Mg, Fe, Mn, and Zn, as well as on TOC in sandy soils in Northeast Thailand.

2. Materials and methods

2.1. Study site, experimental design, and soil sampling

A long-term field experiment was carried out at a research station of the Office of Agriculture and Cooperatives of the Northeast in Khon Kaen, Northeast Thailand (48Q 267649E 1808317N). The land of the present experimental plots at the research station had been converted from forest approximately 50 years ago and planted with experimental field crops, notably cassava and sugarcane, prior to the establishment of the current field experiment in 1995. The field experiment was treated annually with organic residues of different qualities to study their long-term effects on soil quality. The climate of the study site was classified as tropical savanna with an average temperature of 24 °C in winter and 29 °C in summer, with an average rainfall of 224 mm in summer and 1104 mm in the rainy season (Meteorological Department, 2015). The soil was Typic Kandistult, which is an Ultisol according to Soil Taxonomy (2014) (Soil Survey Staff, 2014). The particle size distribution of the topsoil (0–15 cm thick) was 93, 5, and 2% for sand, silt, and clay, respectively (Vityakon et al., 2000), constituting a sandy texture. In addition, the initial properties of the topsoil were strongly acidic (pH H₂O = 5.5) with low cation

exchange capacity (CEC) (3.5 cmol kg⁻¹) and low total organic carbon (0.36%) (Vityakon et al., 2000).

The experiment had five treatments arranged in a randomized, complete block design with 3 replications. The five treatments included (1) no organic residues applied (control) (CT); (2) groundnut (*Arachis hypogaea*) stover (GN), which is considered a high-quality material with high N but low lignin and polyphenol contents; (3) tamarind (*Tamarindus indica*) leaf + petiole litter (TM), which has medium levels of N, lignin, and polyphenols; (4) rice (*Oryza sativa*) straw (RS), which has low levels of N, lignin, and polyphenols but a high cellulose content; and (5) dipterocarp (*Dipterocarpus tuberculatus*) leaf litter (DP), which is considered to be of low quality with a low level of N but high levels of lignin and polyphenols. The treatments were applied at a rate of 10 t DM ha⁻¹ yr⁻¹ to bare soil plots. Each plot was 4 × 4 m². The local organic residues were distributed evenly on the soil surface and manually incorporated to a depth of 15 cm of the experimental plot in early May every year before the start of the rainy season. Weeds were controlled by manual removal from the experimental plots, employing hand hoes.

Soil samples were collected at the end of each experimental cycle (1 year after residue incorporation) during years 7, 9, 16, 19, and 22 of the experiment. Soil samples were randomly collected from the 2 × 2 m² area in the center of each plot at a depth of 0–15 cm. Soil samples from the years before year 22 were retrieved from the archive of the soils of the long-term experiment.

2.2. Chemical analysis

2.2.1. Organic residues

The organic residues used in this study were locally available in Northeast Thailand. The organic residues GN, TM, RS, and DP were oven-dried at 70 °C until their weights were constant. The organic residues used for the year 22 application were prepared for chemical analysis by cutting and grinding to make the samples homogenous. The chemical analyses of the residues were performed in triplicate.

The pH and electrical conductivity (EC) of local organic residues were determined in a suspension of organic residue in deionized water at a ratio of 1:5 (Yusiharni and Gilkes, 2012). The suspensions were shaken on an end-over-end shaker for 16 h (Limwikarn et al., 2018). Total organic carbon (TOC) and total nitrogen (TN) in the organic residues were determined by the dry-combustion method on a CN analyzer (Analytical Jena-analyzer, Multiwin C/N 2100).

Water-soluble elements, including P, K, Ca, Mg, Na, Fe, Mn, Zn, Cl, Si, and Al, in local organic residues were determined according to the method of Yusiharni and Gilkes (2012). Briefly, 0.5 g of ground organic residue was mixed with 100 mL of ultrapure deionized water (18.2 mΩ cm⁻¹) and shaken on an end-over-end shaker for 24 h. The suspensions were filtered through 0.24-μm nylon membrane filters. The concentrations of various water soluble elements were determined using inductively coupled plasma-optical emission spectrometry (ICP-OES) (Analytik Jena, PQ 9000).

Total concentrations of elements (P, K, Ca, Mg, Na, Fe, Mn, Zn, Si, and Al) in organic residues were determined after digestion in concentrated perchloric acid (HClO₄) (Ksawery et al., 2010). The total Cl concentration in the organic residues was not measured because of the use of perchloric acid (HClO₄) in the digestion of organic residues. Moreover, the total concentrations of the other elements were determined by ICP-OES.

2.2.2. Soil samples

Soil pH (pH H₂O) and electrical conductivity (EC) were measured using 1:1 and 1:5 soil to deionized water ratios, respectively (Rayment and Lyons, 2011). Total organic carbon (TOC) was determined by wet combustion according to the Walkley and Black method (Nelson and Sommers, 1996). Available nutrients, including P, K, Ca, Mg, Fe, Mn, and Zn, in soils were extracted by Mehlich-3 solution (Rayment and Lyons, 2011), after which the concentrations were determined by ICP-OES.

2.3. Statistical analysis

Principal component analysis (PCA) was used to identify the distribution of various element compositions of the residues and to group the residues studied based on their chemical properties. An analysis of variance (ANOVA) using the least significant difference (LSD) test was used to determine significant differences in the chemical composition of the residues GN, TM, DP, and RS. Regression analysis was performed to determine the effects of some soil properties on the availability of some plant nutrients. All data were log transformed to meet the requirement of a normal distribution for PCA, ANOVA, and regression analysis at $P < 0.05$ using Statistica software version 8.0 for Windows.

3. Results and discussion

3.1. Characteristics of local organic residues

The studied organic residues were generally acidic, with an average pH (H_2O) ranging from 3.7 in TM to 5.8 in GN and RS (Table 1). TM had the lowest pH (H_2O) due to elevated levels of organic acids, especially tartaric acid (Adeola and Aworth, 2012). The results showed that the pH of organic residues varied widely. When organic residues/wastes were turned to ash or biochar, the pH fell to alkaline ranges ($pH > 7$) (e.g., Yusiharni and Gilkes, 2012; Limwikarn et al., 2018). Pereira et al. (2011) reported that organic residues had acidic properties, but after they were burned, the pH increased. The general acid property of the studied organic residues indicates that their effective use for soil incorporation should take place in conjunction with lime.

The average EC values of the local organic residues ranged between 0.8 and 3.0 mS cm^{-1} (Table 1). They reflect the contents of soluble inorganic solutes in the residues. The lowest EC value was found in DP (0.8 mS cm^{-1}). The highest EC values were found in GN (3.0 mS cm^{-1}), followed by TM (2.5 mS cm^{-1}) and RS (2.3 mS cm^{-1}), indicating that GN, TM, and RS contained high contents of soluble inorganic solutes (Rhoades, 1996).

The average concentrations of TOC for DP, TM, GN, and RS were 42, 40, 39, and 36%, respectively (Table 1). GN and TM, which are leguminous plant-derived residues, had higher total N contents (1.7% for both) than DP and RS (1.0 and 0.4%, respectively) (Table 1). As a result, the average ratios of the C/N ratio for GN, TM, DP, and RS were 22, 23, 40, and 86, respectively (Table 1). The total N contents and C/N ratios have a bearing on the decomposition of these organic residues. Based on the critical C/N ratio of 24, GN and TM can be rapidly mineralized by microorganisms, whereas DP and RS are slow to mineralize, leading to the slow release of plant nutrients to soils (Moritsuka et al., 2004). Even though the C/N ratio of TM was not significantly different from that of GN, the turnover rate of TM was slower than that of GN because TM contained higher concentrations of lignin and polyphenols than GN (Vityakon et al., 2000). Furthermore, a study revealed that RS was more rapidly decomposed than DP because the former contains lower concentrations of lignin and polyphenols than the latter (Vityakon et al., 2000).

3.2. Total element concentrations in organic residues

The average total concentrations in mg kg^{-1} and kg ha^{-1} of various elements in the four residues are shown in Table 2. Principal component

analysis (PCA) of standardized log total concentrations of elements, including N, P, K, Ca, Mg, Na, Fe, Mn, Zn, Si, and Al, for the four types of locally available organic residues showed that the first two components could explain 76% of the variation in the data (Figure 1). Attributes could be allocated into 4 main groups reflecting the biochemical compositions of the organic residues (Figure 1).

The PCA showed that the GN contained high total concentrations (mg kg^{-1}) of N (17343), K (7291), and P (2169) (Table 2). TM had the highest total concentration (mg kg^{-1}) of Ca (19837), followed by N (17420), Mg (5723), Fe (281), Al (168), and Zn (23). The PCA revealed that TM was closely associated with Al (Figure 1). Because of the large surface areas of TM, tamarind leaf and petiole litter were exposed to soils once it fell to the ground (Khanna et al., 1994). Dipterocarp leaf litter had the highest total Si (296 mg kg^{-1}) and Mn (860 mg kg^{-1}) concentrations, whereas RS contained the highest total Na concentration (253 mg kg^{-1}) (Table 2). The results were consistent with other studies that reported that the chemical compositions of organic residues varied depending on the species and plant parts from which residues were derived (e.g., Khanna et al., 1994; Li et al., 2019). In addition, plant residues from different cultivation years were reported to have variations in nutrient concentrations (Oh et al., 2018). Our analysis of residue chemical composition was performed with samples collected and applied in year 22 of the long-term experiment. By comparing the chemical composition, notably N, lignin, and polyphenols, of year 22 with those of other years (i.e., year 1 (Vityakon et al., 2000), year 10 (Samahadthai et al., 2010), and year 13 (Puttaso et al., 2013)), we found that year-to-year variations in each chemical-composition parameter did exist. However, the differences in the chemical composition of the residues were consistent across the four years (e.g., GN, which has the highest N in year 22 also had the highest N in all other years).

3.3. Water soluble element concentrations of local organic residues

The water-soluble element concentrations in mg kg^{-1} and kg ha^{-1} in the four residues are presented in Table 3. The PCA based on standardized log water-soluble concentrations of P, K, Ca, Mg, Na, Fe, Mn, Zn, Cl, Si, and Al (Figure 2) showed that GN had high concentrations (mg kg^{-1}) of water-soluble K (5105) and P (2025), which were higher than those of the other residues. TM had higher concentrations (mg kg^{-1}) of many water-soluble elements, including Ca (7800), Mg (2623), and Zn (13), than the other residues (Table 3). DP had elevated water-soluble concentrations (mg kg^{-1}) of Mn (297), Si (91), and Fe (13). In addition, the PCA showed that RS was situated on the factor 2 axis between Cl, Na, and Si, indicating that RS contained high concentrations of these elements (Figure 2). RS contained high concentrations (mg kg^{-1}) of water-soluble Cl (6894), Na (155), and Si (115) (Table 3). RS is able to absorb Na and Cl ions and accumulates these ions in its tissue (Hussain et al., 2017). In addition, this research revealed that the Cl/Na ratios in the organic residues GN, TM, DP, and RS were not equal to 1, indicating that most of the water-soluble Cl in plant tissue is more likely derived from other salt minerals, such as sylvite (KCl) and chlorocalcite ($KCaCl_3$), than from halite (NaCl) (Limwikarn et al., 2018). Our results indicated that the high-quality organic residue GN had higher water-soluble macronutrient elements P and K than lower-quality residues TM, DP, and RS. The amount of water-soluble micronutrient elements Fe, Mn, and Zn were

Table 1. Selected chemical properties of local organic residues in Northeast Thailand*.

Organic Residue	pH	EC	TOC	TN	C/N
Groundnut stover	5.8 ^a	3.0 ^a	39 ^c	1.7 ^a	22 ^c
Tamarind leaf litter	3.7 ^c	2.5 ^b	40 ^b	1.7 ^a	23 ^c
Dipterocarp leaf litter	4.5 ^b	0.8 ^d	42 ^a	1.0 ^b	40 ^b
Rice straw	5.8 ^a	2.3 ^c	36 ^d	0.4 ^b	86 ^a

* EC = electrical conductivity (mS cm^{-1}); TOC = total organic carbon (%); TN = total nitrogen (%); C/N = carbon to nitrogen ratio. The mean concentration of each property followed by different letters is significantly different at $P < 0.05$ (LSD).

Table 2. Total elemental concentrations in mg kg⁻¹ and kg ha⁻¹ (in parentheses) for local organic residues in Northeast Thailand*.

Element	Groundnut stover	Tamarind leaf litter	Dipterocarp leaf litter	Rice straw
N	17343 ^a (173)	17420 ^a (174)	10380 ^b (104)	4143 ^c (41)
P	2169 ^a (22)	763 ^b (7.6)	480 ^d (4.8)	655 ^c (6.6)
K	7291 ^a (73)	6056 ^a (61)	3334 ^b (33)	5513 ^a (55)
Ca	3490 ^b (35)	19837 ^a (198)	4130 ^b (41)	1222 ^c (12)
Mg	1750 ^b (18)	5723 ^a (57)	1343 ^c (13)	597 ^d (6.0)
Na	141 ^b (1.4)	61 ^c (0.61)	48 ^c (0.48)	253 ^a (2.5)
Fe	261 ^{ab} (2.6)	281 ^a (2.8)	227 ^{ab} (2.3)	151 ^b (1.5)
Mn	95 ^b (0.95)	93 ^b (0.93)	860 ^a (8.6)	855 ^a (8.6)
Zn	15 ^a (0.15)	23 ^a (0.23)	4.8 ^b (0.048)	14 ^a (0.14)
Si	36 ^c (0.36)	186 ^b (1.9)	296 ^a (3.0)	175 ^b (1.8)
Al	186 ^a (1.9)	168 ^a (1.7)	159 ^a (1.6)	14 ^b (0.14)

* Mean total concentrations of each element followed by different letters are significantly different at P < 0.05 (LSD).

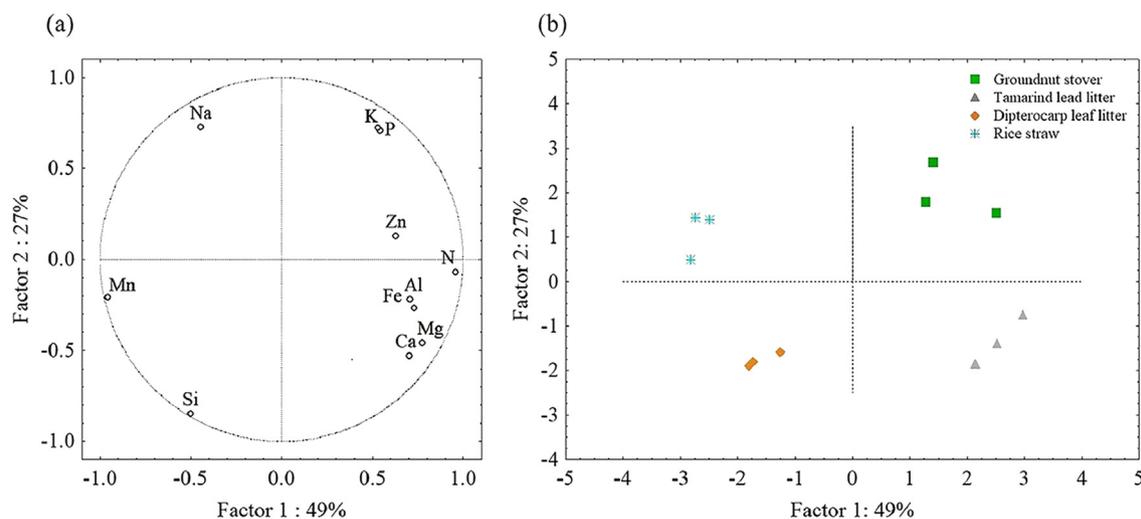


Figure 1. Principal component analysis of standardized log total elemental concentration for local organic residues in Northeast Thailand: (a) distribution of plant nutrient elements (variables) and (b) organic residues (cases).

elevated in the medium- and low-quality organic residues TM and DP compared to the high-quality GN because these elements are more soluble in acidic conditions (Sukitprapanon et al., 2018). The acidity of these organic residues is presented in section 3.1. The relative contents of water-soluble Si in RS and GN were higher than those in TM and DP (Table 4) because Si is more soluble in the more alkaline conditions of GN and RS than in the acidic conditions of TM and DP (Zhu et al., 2018).

A critical factor controlling the solubility of various elements in plant tissues is the form of minerals/chemical compounds of these elements in organic residues (Yusiharni and Gilkes, 2012). Another factor is mineralization, which is a subprocess of decomposition, but mineralization is only required for the elements that are constituents of organic compounds in plant tissues (Palm et al., 2001). Palm et al. (2001) and

Kunlanit et al. (2014) suggested that mineralization of organic forms of plant nutrient elements in organic residues is regulated by the amount of total N, lignin, polyphenol, and cellulose.

3.4. Long-term effects of contrasting biochemical quality organic residues on plant available nutrients in sandy soil

The long-term temporal effects of contrasting biochemical-quality organic residues on pH, EC, TOC, and plant available nutrients, including P, K, Ca, Mg, Fe, Mn, and Zn, are presented in Figure 3. The temporal pattern of soil pH of the unamended sandy soil showed a decline to below pH 4.5 from year 16 onwards (Figure 3a). The sandy soils amended with organic residues had higher pH values than did the

Table 3. Water soluble element concentrations in mg kg⁻¹ and kg ha⁻¹ (in parentheses) for local organic residues in Northeast Thailand*.

Element	Groundnut stover	Tamarind leaf litter	Dipterocarp leaf litter	Rice straw
P	2025 ^a (20)	277 ^c (2.8)	163 ^c (1.6)	413 ^b (4.1)
K	5105 ^a (51)	2013 ^b (20)	520 ^c (5.2)	1818 ^b (18)
Ca	1552 ^b (16)	7800 ^a (78)	761 ^c (76)	336 ^c (3.4)
Mg	1274 ^b (13)	2623 ^a (26)	1098 ^b (11)	399 ^c (4.0)
Na	87 ^b (0.87)	20 ^c (0.20)	3.4 ^d (0.034)	155 ^a (1.6)
Fe	7.3 ^c (0.073)	7.5 ^c (0.075)	13 ^a (0.13)	10 ^b (0.10)
Mn	24 ^c (0.24)	51 ^b (0.51)	297 ^a (3.0)	309 ^a (3.1)
Zn	5.3 ^c (0.053)	13 ^a (0.13)	3.6 ^c (0.036)	11 ^b (0.11)
Cl	4964 ^b (50)	4286 ^c (43)	1750 ^d (18)	6894 ^a (69)
Si	16 ^b (0.16)	21 ^b (0.21)	91 ^a (0.91)	115 ^a (1.2)
Al	7.7 ^b (0.077)	10 ^a (0.10)	6.9 ^c (0.069)	1.0 ^d (0.010)

* Mean water soluble concentrations of each element followed by different letters are significantly different at $P < 0.05$ (LSD).

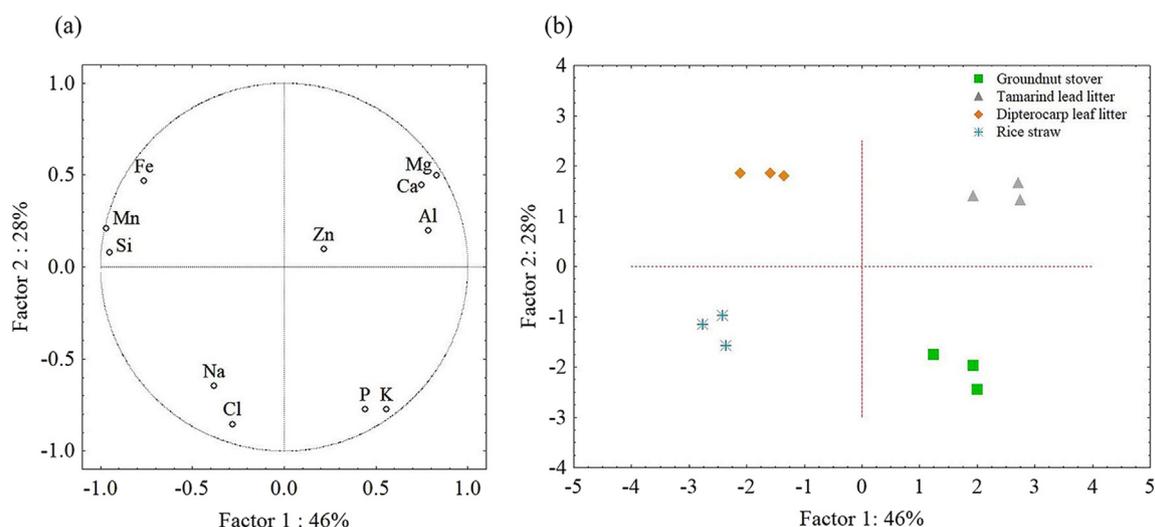


Figure 2. Principal component analysis of standardized log water soluble element concentrations for local organic residues in Northeast Thailand: (a) distribution of plant nutrient elements (variables) and (b) organic residues (cases).

unamended soil (Figure 3a). During 22 years of the long-term experiment, the soil pH values were stable, ranging from 5.6 to 5.7, and 5.5 to 5.7 for DP- and RS-treated soils, respectively (Figure 3a). The soil pH value under GN-treated soil slightly decreased from 5.7 in year 7 to 5.1 in year 22 (Figure 3a) because GN contained high concentrations of total N (Table 2). On the other hand, TM application significantly increased soil pH over the other treatments (Figure 3a).

The pH decline is due to the leaching loss of basic cations and the hydrolysis of Fe and Al (hydr)oxides in the soil (Sparks, 2002). Negative charges on the organic colloidal surface can adsorb protons (H^+) in soil solution. However, the application of high N-bearing organic residues to soils results in enhanced nitrification, which liberates H^+ in soil solutions (Cleemput and Boeckx, 2006). In addition, the increase in the soil pH

value after the application of organic residues, in particular TM (Figure 3a), is likely due to the effect of ash alkalinity originating from added organic residues (Slattery et al., 1991; Noble et al., 1996). Organic residues and litter have various ash-alkalinity contents, expressed as calcium carbonate equivalents, which have the capacity to increase soil pH (Slattery et al., 1991; Noble et al., 1996). Noble et al. (1996) reported that ash alkalinity has a positive association with Ca concentrations in plant residues. This positive association indicates that organic residues, particularly TM, contain elevated contents of ash alkalinity, as shown by the highest Ca concentrations of 19837 mg kg⁻¹ under TM, which was approximately 5–16 times higher than the other residues used in this study (Table 2). Our results also indicate that long-term applications of low-quality organic residues only maintain the level of soil pH, but they

Table 4. Relative contents of water-soluble elements as a proportion of the total element contents in local organic residues from Northeast Thailand*.

Element	Groundnut stover	Tamarind leaf litter	Dipterocarp leaf litter	Rice straw
P	0.93 ^a	0.36 ^c	0.34 ^c	0.63 ^b
K	0.70 ^a	0.34 ^b	0.16 ^c	0.33 ^b
Ca	0.45 ^a	0.40 ^a	0.19 ^b	0.27 ^b
Mg	0.73 ^a	0.46 ^b	0.82 ^a	0.67 ^a
Na	0.46 ^a	0.53 ^a	0.09 ^b	0.65 ^a
Fe	0.03 ^b	0.03 ^b	0.06 ^a	0.06 ^a
Mn	0.25 ^c	0.56 ^a	0.35 ^b	0.36 ^b
Zn	0.40 ^b	0.65 ^{ab}	0.70 ^a	0.79 ^a
Si	0.43 ^{ab}	0.12 ^c	0.31 ^b	0.66 ^a
Al	0.06 ^a	0.09 ^a	0.04 ^a	0.08 ^a

* Mean relative contents of each element followed by different letters are significantly different at $P < 0.05$ (LSD).

do not increase the soil pH value. Furthermore, the application of high-quality organic residues with high N should be accompanied by lime to counter the soil pH decrease.

The electrical conductivity (EC) values of organic, residue-treated soils were higher than those of their untreated counterparts. The EC values were highest under TM, followed by GN, and they generally increased with time (Figure 3b). TM and GN contained high contents of water-soluble elements, particularly P, K, Ca, and Mg (Figure 2). Yusiharni and Gilkes (2012) reported that the differences in soluble salt contents (e.g., halides, carbonates, hydroxides, and oxides) in organic residues contribute to the differences in EC values in soils.

The total organic carbon (TOC) of untreated soils decreased from 0.31% in year 7 to 0.15% in year 22 (Figure 3c). The TOC of all organic, residue-treated soils largely fluctuated over time during the 22-year period. Nevertheless, the TOC contents under the TM treatment were higher than those under the other treatments (Figure 3c). This phenomenon confirmed the earlier findings at the end of year 13 of the same long-term experiment (Puttaso et al., 2013).

Puttaso et al. (2013) reported that the main location for carbon (C) storage in the soil matrix of the studied sandy soils is in soil aggregates (0.053 - > 2 mm), which store an average of 58% TOC in soils treated with various organic residues. Microaggregates (0.053–0.25 mm) are the prominent aggregate sites that store 41% TOC on average. In addition, TM-treated soil has the highest C stored in this location (49%), followed by GN-treated soil (41%) (Puttaso et al., 2013). Both TM and GN have both labile (e.g., sugar and cellulose) and recalcitrant (e.g., lignin) C compounds, as well as medium to high contents of N. Puttaso et al. (2013) suggested that C compounds, both labile and recalcitrant, in organic residues interacted with N in promoting stabilization in microaggregates. Palm et al. (2001) reported that the chemical compositions (e.g., total N, lignin, and polyphenol) of organic residues influence the accumulation of organic carbon in soils. Another plausible factor contributing to high TOC in TM soil is the fact that TM contains high concentrations of allelopathic compounds (e.g., phenolic compounds, tannins, flavonoids, and alkaloids) (Parvez et al., 2003). Allelopathic compounds have an adverse effect on bacterial and fungal activities (Lorenzo et al., 2013). A recent study by Lawongsa et al. (2016) showed that tannins are one of the most important allelopathic compounds in TM that deter microbial activities in soils.

The concentration of available P in residue-treated soils ranged from medium to high levels, whereas that in the control soil was considered low according to the established criteria for Mehlich-3 extractable P (Mylavarapu et al., 2017). In year 22, RS-treated sandy soil had the highest contents of available P (46 mg kg⁻¹), followed by GN (39 mg kg⁻¹), DP (30 mg kg⁻¹), TM (29 mg kg⁻¹), and the control (CT) (24 mg kg⁻¹) (Figure 3d). Both GN and RS had high-relative contents of water-soluble P (Table 4). The available P concentrations in RS- and GN-treated soils did not increase after 22 years of annual application, whereas those in DP and CT soils decreased compared to the earlier

period (year 7) (Figure 3d). Sukitprapanon et al. (2019) reported that P can be adsorbed by organic matter and fixed by Fe and Al (hydro)oxides in soil under acidic conditions. For TM-treated soils, available P increased from 23 mg kg⁻¹ in year 7–29 mg kg⁻¹ in year 22 (Figure 3d) because soil pH increased from acidic conditions in year 7 to neutral conditions in year 22 (Figure 3a). Notably, the available P contents in the untreated soils in years 7, 9 and 16, were higher than those in TM-treated soils (Figure 3d). These results of available P contents corroborate those of Rungthong (2016), who found the available P contents in untreated soil of year 17 (21 mg kg⁻¹) to be higher than those of TM-treated soils (17 mg kg⁻¹). In addition, the same work reported that untreated sandy soils have a higher population of phosphate-solubilizing bacteria, such as *Pseudomonas*, *Azospirillum*, *Burkholderia*, and *Bacillus*, than TM-treated soils (Rungthong, 2016). It has been reported that increases in available P in acidic soils occur when acidic soils are amended with organic residues and liming materials (Eduah et al., 2019).

The available K contents in residue-treated soils, ranging from 23 to 61 mg kg⁻¹, were considered to be at medium levels (Mylavarapu et al., 2017) and were higher than those in the control (17 mg kg⁻¹) (Figure 3e), indicating that K is released to the soils via decomposition of organic residues. This study revealed that although organic residues had been added yearly for over 2 decades, the levels of available K in sandy soils were not significantly increased (Figure 3e). The K released to the soils from organic residues is either leached down soil profiles or adsorbed onto the surface of soil constituents, such as soil organic matter (Wang and Huang, 2001) and clay mineral kaolinite (Khawmee et al., 2013). Organic matter is the most important soil constituent affecting K retention, because it increases CEC. Kaolinite is the dominant clay mineral in highly weathered tropical soils (e.g., Ultisols) (Khawmee et al., 2013). Khawmee et al. (2013) reported that kaolinite in Thai Ultisols contains a net-negative charge under natural conditions and has limited capacity to adsorb cations. Since the tropical, sandy soil used in this study is an Ultisol and contains low levels of both soil organic matter (0.36%) and clay (2%) (Vityakon et al., 2000), the soil has a low capacity to retain K. Consequently, leaching is likely the major process for K loss from the soil.

Although the available Ca concentrations in all soils (range 5.4–297 mg kg⁻¹) were considered low (New Jersey Agricultural Experiment Station, 2020), those in TM and GN soils increased approximately 94 and 35%, respectively, in year 22 compared to year 7, while those in the other treatments, such as CT, DP, and RS, decreased approximately 93, 53, and 19%, respectively (Figure 3f). The highest concentration of available Ca (297 mg kg⁻¹) that occurred in the TM treatment after 22 years of yearly application was due to the high Ca concentration in the TM residues (Table 2). Interestingly, our results show that the average, available-Ca contents in GN-treated soils were reduced from 149 mg kg⁻¹ in year 16–88 mg kg⁻¹ in year 22 (Figure 3f). The decrease in available Ca concentration was due to increased soil acidity in later years under continuous applications of the high-quality organic residue GN

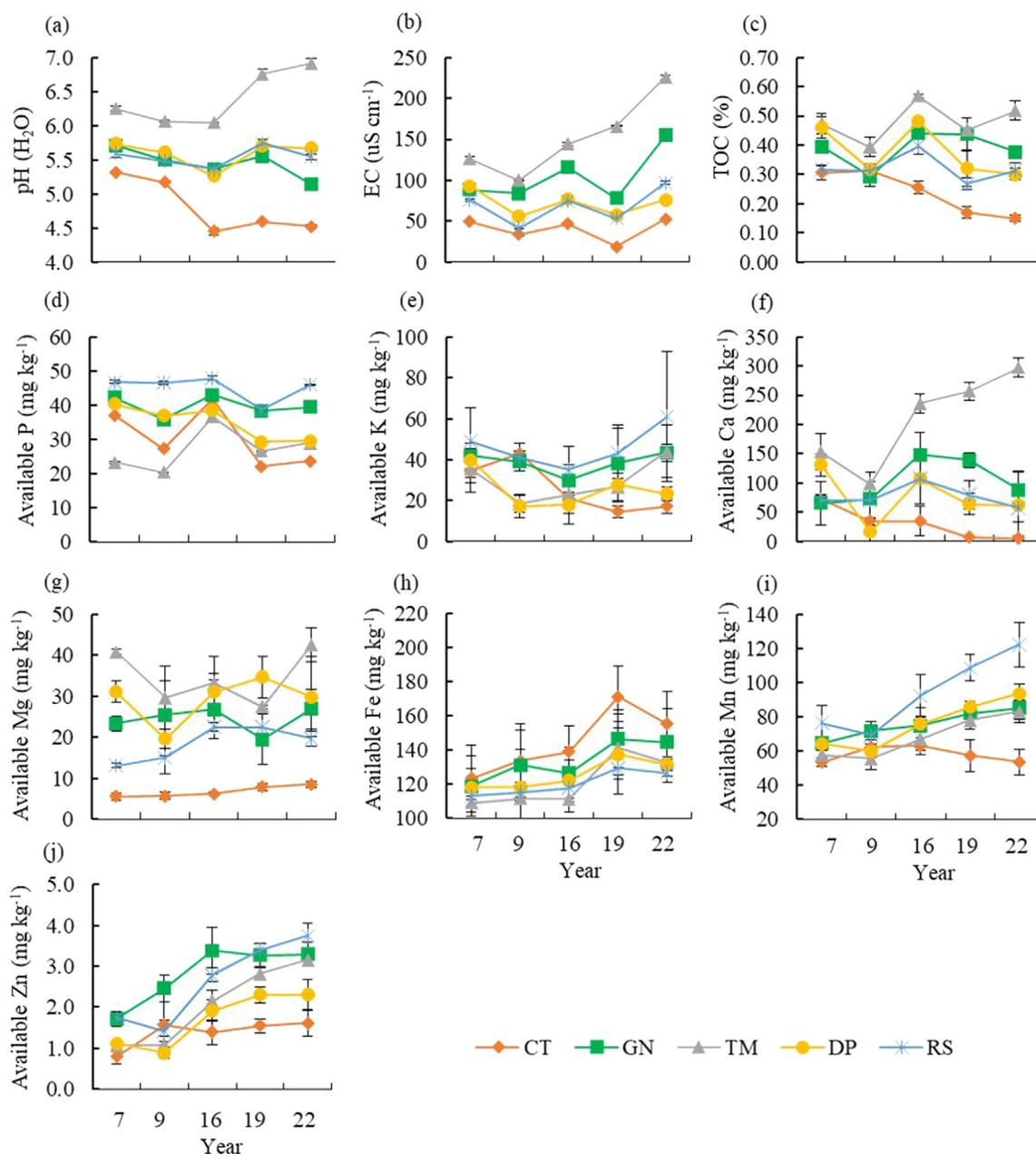


Figure 3. Temporal patterns of soil chemical properties on nutrient availabilities as affected by long-term application of organic residues in tropical sandy soils: (a) soil pH, (b) electrical conductivity (EC), (c) total organic carbon (TOC), (d) available phosphorus (P), (e) available potassium (K), (f) available calcium (Ca), (g) available magnesium (Mg), (h) available iron (Fe), (i) available manganese (Mn), and (j) available zinc (Zn). CT = control, GN = groundnut stover, TM = tamarind leaf litter, DP = dipterocarp leaf litter, and RS = rice straw. The error bars are the standard deviation of the means.

(Figure 3a). Regarding available Mg, its soil concentrations were considered to be at a medium level (Mylavarapu et al., 2017) and were stable after 22 years of organic residue application (Figure 3g). Magnesium is weakly bound to negative charges on the soil surface. Consequently, Mg is more soluble in soil solution than Ca and K and can leach down acidic soil profiles (Maquire and Cowan, 2002). In addition, this study revealed that the available Mg had a positive relationship with available Ca in the sandy soil ($R^2 = 0.41$) ($P < 0.05$) (Figure 4a), indicating that available Ca and Mg concentrations in the sandy soil increased hand-in-hand as a result of the incorporation of organic residues.

The available Fe concentrations in all soils ranged between 103 and 171 mg kg⁻¹, which was considered to be at a medium level (Zbiral, 2016). The control soil had the highest available Fe contents, which increased from 124 mg kg⁻¹ in year 7–155 mg kg⁻¹ in year 22

(Figure 3h). The available Fe contents in the sandy soil under GN treatment increased compared to other amended soils (Figure 3h) because the soil pH value of GN treatment decreased with time (Figure 3a). The bivariate relationship showed that available Fe had a negative relationship with soil pH ($R^2 = 0.20$) ($P < 0.05$) (Figure 4b). This result indicates that the contents of available Fe in the sandy soil increase when the soil pH decreases. Sukitprapanon et al. (2018) reported that low-soil pH induces the solubility of Fe and potentially toxic elements, such as Al and heavy metals, in soil solution.

The long-term soil incorporation of local organic residues had positive effects on increasing concentrations of available Mn and Zn (Figures 3i and 3j). After 22 years of yearly application of organic residues, the available Mn concentrations were at a medium level (Zbiral, 2016). In addition, it was found that long-term incorporation of organic residues enhanced the level of available Zn from a low level in year 7 to

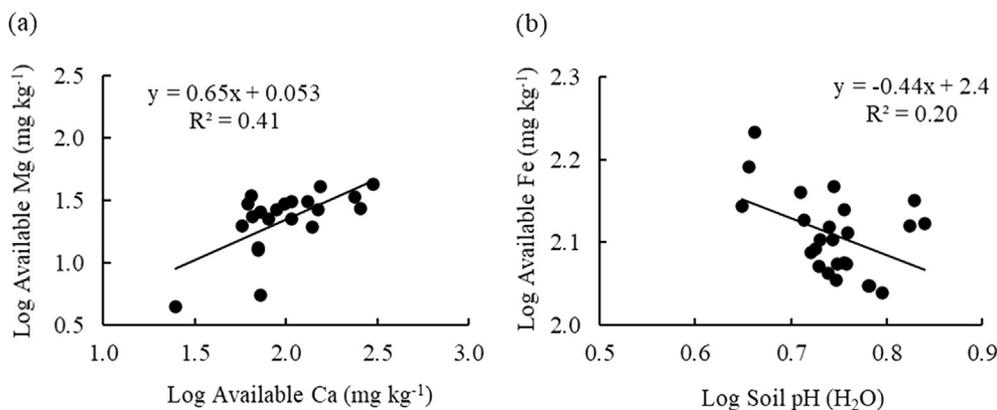


Figure 4. Bivariate relationships between log available Ca and log available Mg (a) and log soil pH (H₂O) and log available Fe (b) for long-term applications of local organic residues with different biochemical properties in tropical sandy soils used in this research.

a medium level in year 22 based on the published critical values of Zbiral (2016) (Figure 3j). In year 22, the RS-treated soil contained the highest amounts of available Mn (122 mg kg⁻¹) and Zn (3.8 mg kg⁻¹) (Figures 3i and 3j). The results indicate that long-term applications of the low-quality organic residue RS led to accumulations of trace elements (e.g., Mn and Zn) in the tropical, acidic, sandy soil. The concentrations of available Mn and Zn in the soil were certainly reflected by the nutrient composition of organic residues added to the soil (Table 2). In addition to the contributions of these trace elements, Mn and Zn, to sandy soil by organic residues, soil can retain trace elements through adsorption by soil constituents, such as clay minerals and soil organic carbon, resulting in their higher concentrations in organic, residue-treated soils than in untreated soil (Ondrasek and Rengel, 2012; Khawmee et al., 2013).

4. Conclusions

The locally available organic residues in Northeast Thailand vary widely in elemental composition depending on the species and part of the plant. All local organic residues were commonly acidic and contained plant nutrients that can be used as alternative sources of nutrients. The high-quality organic residue GN was a suitable source for supplying macronutrients, such as N, P, and K, while the lower-quality counterparts TM, DP, and RS were suitable for supplying other macronutrients, such as Ca and Mg, and micronutrients, such as Mn and Zn. The soil pH was raised under the application of organic residues, particularly TM, which is likely due to the ash-alkalinity effect. The addition of GN with high N contents decreased the soil pH due to H⁺ originating from the nitrification process. Long-term incorporation of medium-quality organic TM residues with outstandingly high Ca, high lignin, and high polyphenol contents increased TOC, available P, Ca, and Mg in tropical, sandy soil. Long-term additions of low-quality DP and RS increased available Mn and Zn. Long-term addition of organic residues did not increase the available K. The implication of this finding is that farmers and agricultural extensions need to understand the nature of organic residues that are available on farms. In addition, lime should be used to raise the level of soil pH in the case of using high-quality organic residues, such as GN, which lowers the soil pH when applied repeatedly.

Declarations

Author contribution statement

Tanabhat-Sakorn Sukitprapanon: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Metawee Jantamenchai: Performed the experiments; Analyzed and interpreted the data.

Duangsamorn Tulaphitak: Contributed reagents, materials, analysis tools or data.

Patma Vityakon: Conceived and designed the experiments; Performed the experiments; Wrote the paper.

Funding statement

This work was supported by the Thailand Research Fund (Project code: MRG6180149) and a New Researcher Scholar from Khon Kaen University. Writing of the manuscript was partly funded by TRF-DAAD PPP grant 2018.

Data availability statement

Data included in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

We gratefully acknowledge staff from Khon Kaen University for analytical advice, Professor Dr. Robert Gilkes from School of Agriculture and Environment, The University of Western Australia, Professor Dr. Georg Cadisch from the Institute of Agricultural Sciences in the Tropics, University of Hohenheim, and the anonymous reviewers for providing constructive suggestions for this manuscript.

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