Combined use of contrasting quality organic residues and chemical fertilizers for corn growth in a sandy soil

Sisavanh Xayavong[1,2], Somchai Butnan[2,3*] and Patma Vityakon[1,2]

ABSTRACT: A plant bioassay experiment was conducted to evaluate the effects of residue quality (chemical composition with respect to N, lignin, and polyphenol contents), chemical fertilizers, and their interactions, on plant nutrient availability and growth. Corn plants were grown in pots containing sandy soils taken from a long-term field experiment in which five levels of contrasting quality residues were applied annually for 20 years. The residue treatments included: (i) unamended (control, CT), (ii) rice straw (RS), (iii) groundnut stover (GN), (iv) dipterocarp freshly fallen leaf litter (DP), and (v) tamarind freshly fallen leaf and petiole litter (TM). The soils from the field experiment were treated with 2 different chemical fertilizer management practices with (70.3 N, 30.7 P, and 58.4 K kg/ha) or without fertilizers. Under the sole residue treatments, only high-quality GN [N-rich (21 g/kg)] produced a significantly higher biomass than CT. However, for the residue plus fertilizers treatments, all the residues significantly increased biomass relative to CT, with the highest biomass found in GN. Similar results were found in plant uptake of N and P. TM did not enhance growth to the same extent as GN due to the lower quality of TM [low N content (12 g/kg) and high polyphenols]. For the high-K residues GN (25 g/kg) and RS (14), GN had resulted in lower concentration and uptake of K in the plants than RS. For low-K residues, TM (6 g/kg) and DP (4), TM produced a lower concentration and uptake of K than DP. Both legume residues had a high Ca content (21 and 35 g/kg, respectively). This produced a high Ca/K ratio of 2 and 7 under GN and TM, respectively. These values were higher than the Diagnosis and Recommendation Integrated System (DRIS) norm ratio of 0.3. The antagonistic effects of Ca on K are discussed.
Keywords: DRIS norm, long-term organic residue application, nutrient antagonism, nutrient availability, secondary nutrients

Introduction

Organic amendments have been shown to improve soil fertility and plant growth, as well as soil C sequestration (Vityakon, 2011). However, the sole use of organic amendments may not meet crop nutritional requirements, due partly to low synchronization between nutrient release from the organic residues and crop uptake (Mucheru-Muna et al., 2007). Nutrient release from chemical fertilizers can usually be more readily synchronized with crop needs (Palm et al., 1997). However, the overuse of chemical fertilizer has negative effects on soil fertility, such as a decline in soil microbiological fertility (e.g., microbial diversity) and physical fertility (e.g., increasing soil hardness) (Zhu et al., 2005). Chemical fertilizer derived compounds leaked into the environment can result in groundwater contamination via leaching and atmospheric pollution, including greenhouse gas (GHG) effects via volatilization and GHG emissions (Zhu et al., 2005; Townsend and Howarth, 2010; Fageria, 2014). The combined use of organic materials and chemical fertilizers may address the problems of synchronization of nutrient release and plant uptake, human

1 Land Resources and Environment Section, Department of Plant Science and Agricultural Resources, Faculty of Agriculture, Khon Kaen University, Khon Kaen 40002, Thailand
2 Soil Organic Matter Management Research Group, Khon Kaen University
3 Plant Science Section, Faculty of Agricultural Technology, Sakon Nakhon Rajabhat University, Sakon Nakhon 47000, Thailand
* Corresponding author: sbutnan@snru.ac.th

diseases and environmental pollution, because soil organic matter possesses high nutrient holding capacity (Vityakon, 2011). Currently, the relative advantages and disadvantages of organic materials and chemical fertilizers are still the subject of debate. In addition, studies of the long-term effects of organic residue application on plant growth, particularly in Thailand, are limited.

This study hypothesized that combining of organic residues and mineral fertilizers has a more pronounced effect on the improvement of soil fertility and plant growth than sole organic amendments or sole chemical fertilizer use. The potential positive effects of the combined application of organic residues and chemical fertilizers is due to the interaction between the contrasting quality organic residues and chemical fertilizers. The objective of this study was to investigate the effects on soil properties and plant growth of contrasting quality organic amendments when used alone over a long period (20 years) of annual application, compared with their use in combination with chemical fertilizers.

Materials and methods

Plant bioassay experiment

The plant bioassay experiment was conducted under greenhouse conditions during September-December 2015. A two-way factorial arrangement (5 categories of residue × 2 chemical fertilizer treatments) in a completely randomized design with four replications was used. The studied soil used was the Korat series (isohyperthermic Typic Oxyaquic Kandiustults) which is a coarse-textured and infertile soil (93.4, 4.6, and 2.1% w/w of sand, silt, and clay contents, respectively) (Vityakon et al., 2000). The studied soils had been treated with contrasting quality organic residues following Puttaso et al. (2011) who modified the category of residue quality from the classification of Palm et al. (2001). The classification of organic residue quality was with respect to concentrations (g/kg) of N, lignin (L), and polyphenols (PP). Organic residue treatments employed in this study included (i) unamended (control, CT), (ii) low quality-rice straw (RS) (4.9 N, 26 L, and 8.3 PP) , (iii) high quality-groundnut stover (GN) (20.9 N, 69 L, and 12.3 PP), (iv) low quality-dipterocarp freshly fallen leaf litter (DP) (6 N, 246 L, and 69.3 PP), and (v) intermediate quality-tamarind freshly fallen leaf and petiole litter (TM) (11.9 N, 161 L, and 38.8 PP). The soils which had been treated with these contrasting quality residues were taken from a long-term field experiment (16°20´N; 102° 49´E) in which the residues had been applied yearly for 20 years. The two chemical fertilizer treatments were: no chemical fertilizer applied (-F) and fertilizer (+F) applied at the recommended rates of 70.3 N, 30.7 P, and 58.4 K kg/ha. One and a half kg of air-dry soil was placed in individual plastic pots (d = 14 cm, h = 12.5 cm, v = 1662 cm^3). Corn (*Zea may*) was grown in these pots as the test plant. The period of growth of the corn plants was 40 days.

Four corn seeds (variety Pacific 339) were planted into each pot. Seedlings were thinned to two per pot at 14 days after planting (DAP). Soil moisture content of each pot was adjusted daily by weighing the whole pot and adding distilled water to a predetermined weight, to maintain a 70% water holding capacity (WHC) (soil moisture at WHC = 16.8-19.3% w/w). At 40 DAP the shoot biomass of corn was harvested, followed by soil sampling. The soil samples were air-dried and screened through a 2-mm sieve in preparation for soil chemical analysis.

Laboratory analyses

Plant residue analysis consisted of total C by the Walkley and Black wet digestion method, total N by micro-Kjeldahl, lignin and cellulose by the acid-detergent fiber method (Van Soest and Wine, 1968), and total extractable polyphenols according to the Tropical Soil Biology and Fertility Handbook (Anderson and Ingram, 1993).

Corn shoot biomass samples were oven-dried to a constant weight at 70°C. The dried shoot samples were ground to pass through a 0.5-mm mesh sieve for tissue nutrient analysis. Tissue total N concentration was determined on a TN analyzer (multi N/C® 2100S, Analytik Jena, Germany). Prior to determination of tissue P, K, Ca and Mg concentrations, the plant samples were ashed at 550°C for 3 h. Tissue P concentration was extracted with vanadomolybdate solution and measured on a spectrophotometer, while K, Ca, and Mg concentrations were extracted in 1 *N* HCl. These tissue nutrient concentrations were measured on a spectrophotometer (Flame AAS nova ® 350, Analytik Jena, Germany) for Ca^{2+}, and Mg^{2+} under atomic absorption mode, and for K^{+} under flame photometry mode.

Statistical analysis

Two-way analysis of variance based on a factorial arrangement and a completely randomized design was used to estimate the effects of residue quality, chemical fertilizers, and their interactions on dry biomass, tissue nutrient concentrations, and nutrient uptakes of corn shoot. Differences between the treatment means were compared using Tukey's Studentized Range Test. These statistical analyses were performed using Statistix version 8.0 (Analytical Software, FL, USA). Curve plotting and fitting, as well as the calculations of regression equation and coefficient of determination (r^2) were performed using Sigma Plot software version 12.5 (SYSTAT software, Inc., Chicago, IL, USA). Significant differences are at $p \leq 0.05$.

Results

Corn growth

Significant interactions between residue type and chemical fertilizers were recorded (**Table 1**). In the sole residue amendments (-F), only the GN treatment resulted in a significantly higher corn shoot biomass relative to the control (**Figure 1**). When combined with chemical fertilizers (+F), all the residue treatments gave a significantly higher shoot biomass than the control, with the GN treatment giving the highest shoot biomass.

Table 1 Analysis of variance (ANOVA) pertaining to the effects of the different organic residues, chemical fertilizers, and their interactions on dry weight, nutrient concentrations, and nutrient uptakes of corn shoots.

Source of variance	df	Shoot dry weight (g/pot)	Nutrient concentrations in corn shoot tissue (g/kg)					Nutrient uptake of corn shoot (mg/pot)				
			N	P	K	Ca	Mg	N	P	K	Ca	Mg
Residues type (R)	4	***	*	*	***	***	***	***	***	***	***	***
Chemical fertilizers (F)	1	***	***	ns	ns	***	***	***	***	***	***	***
R × F	4	***	ns	ns	ns	***	***	**	ns	***	**	***

* p ≤ 0.05;** p ≤ 0.01; *** p ≤ 0.001; ns, not significantly different (F-test).

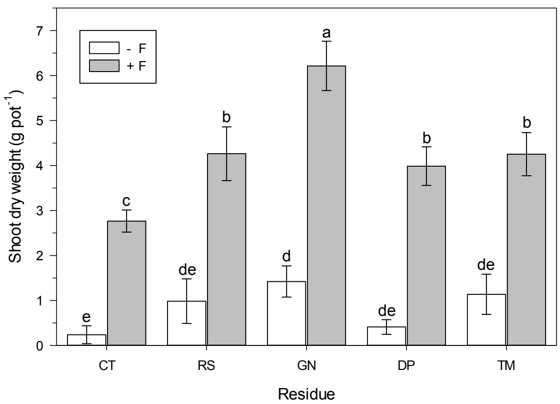

Figure 1 Dry weights of corn shoots grown in Korat soil in a pot experiment as affected by different organic residue amendments, i.e., unamended (control, CT), rice straw (RS), groundnut stover (GN), dipterocarp freshly fallen leaf litter (DP), and tamarind freshly fallen leaf and petiole litter (TM), without (-F) or with (+F) chemical fertilizers. Bars accompanied by similar letters are not significantly different ($p \leq 0.05$) (Tukey's Multiple Comparison Test). Error bars represent standard error of the mean (SEM).

Corn tissue nutrient concentrations and ratios, and nutrient uptake

Significant interactions of residue × chemical fertilizers were found for tissue concentrations of Ca and Mg, and uptakes of N, K, Ca, and Mg in the corn shoots (**Table 1**). Significantly higher tissue nutrient concentrations in the +F than -F was reflected in Ca under GN and TM, and in Mg for all residues with the exception of RS (**Table 2**). Overall, significantly higher nutrient uptakes in +F than -F were found for all investigated nutrients of all residues, except for K in DP and Mg in CT (**Table 3**).

Amongst the residue treatments in both -F and +F, the significantly higher nutrient concentrations than the controls were found in certain residues; these were K of RS; Ca of GN and TM; and Mg of GN, DP, and TM (**Table 2**).

Table 2 Nutrient concentrations in corn shoots grown in a coarse-textured Korat soil, as affected by contrasting quality plant residues and chemical fertilizer managements, without and with chemical fertilizers.

Residues†	Nutrient concentrations in corn shoot tissue (g/kg)									
	N		P		K		Ca		Mg	
	-F ‡	+F	-F	+F	-F	+F	-F	+F	-F	+F
CT	10.2 ±0.5 ab §	11.25±0.7 a	3.99±0.5	5.04±1.1	2.43±0.6 c	3.57±0.3 bc	3.60±0.5 e-c	2.33±0.1 ef	2.77±0.5 c	0.87± 0.1 d
RS	8.52±0.7 b	10.37±0.4 ab	2.97±0.2	4.44±1.0	5.82±0.2 ab	6.59±0.4 a	2.78±0.2 d-f	2.25±0.1 f	2.80±0.1 c	3.07±0.2 bc
GN	9.31±0.3 ab	9.75±0.1 ab	3.45±0.3	3.45±0.2	2.60±0.3 c	2.83±0.1 c	6.10±0.4 b	3.95±0.2 cd	4.01±0.2 ab	2.74± 0.2 c
DP	8.90±0.4 b	10.75±0.4 ab	4.10±0.9	3.45±0.4	2.54±0.4 c	2.23±0.8 c	4.05±0.2 cd	2.95±0.3 d-f	5.18±0.1 a	2.87±0.3 bc
TM	9.96±0.6 ab	11.37±0.3 a	2.48±0.9	2.57±0.3	1.74±1.1 c	1.83±0.6 c	8.43±0.2 a	4.88±0.3 bc	4.52±0.2 a	2.82±0.3 bc
p-value	0.002		0.178		< 0.001		< 0.001		< 0.001	
F-test	**		ns		***		***		***	
C.V. (%)	9.41		36.46		34.23		13.24		15.85	

* $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$; ns, not significantly different (F-test).

† CT = control (unamended); RS = rice straw; GN = groundnut stover; DP = dipterocarp leaf litter; and TM = tamarind leaf litter; ‡ -F = without chemical fertilizer application; +F = with chemical fertilizer application; § Means of each nutrient element followed by similar letters are not significantly different at $p \leq 0.05$ (Tukey's Studentized Range Test). § Values are mean ± standard error of the mean.

For -F, significantly higher nutrient uptakes in residue amendments than the control were found in the following parameters: N of GN, Ca and Mg of GN and TM (**Table 3**). In relation to +F, the significantly higher uptake in the residue amended treatments than the control was found in N, Mg, and Ca of all residues with the exception for Ca of RS. In addition, under the +F, GN and RS had significantly higher P and K uptake, respectively, than the control. Meanwhile, GN had the highest N and P uptake under the +F treatments.

Table 3 Nutrient uptake of corn shoots grown in coarse-textured Korat soil as affected by contrasting quality plant residues and chemical fertilizer managements, without and with chemical fertilizers.

Resi-dues†	Nutrient uptake of corn shoot (mg/pot)									
	N		P		K		Ca		Mg	
	-F ‡	+F	-F	+F	-F	+F	-F	+F	-F	+F
CT	2.56±1.1 e §	31.0±1.7 c	0.95±0.4 e	13.7±2.7 bc	0.46±0.2 e	9.93±1.1 bc	0.98±0.4 e	6.43±0.5 cd	0.52±0.2 d	2.43±0.3 cd
RS	8.34±2.0 de	43.9±1.7 b	3.01±0.9 e	18.4±3.1 ab	5.72±1.4 c-e	28.2±2.7 a	2.63±0.6 de	9.65±1.0 bc	2.66±0.6 cd	13.1±1.2 ab
GN	13.3±1.9 d	60.6±2.3 a	4.80±0.5 de	21.4±1.5 a	3.62±0.5 c-e	17.6±1.2 b	8.83±1.6 bc	24.3±1.8 a	5.72±0.8 c	16.9±1.0 a
DP	3.60±0.6 de	42.8±2.4 b	1.57±0.2 e	13.6±0.4 bc	1.04±0.3 de	9.10±3.1 b-d	1.70±0.4 de	11.8±1.0 b	2.16±0.5 cd	11.5±1.7 b
TM	11.7±3.0 de	48.3±2.6 b	2.56±0.7 e	10.8±1.1 cd	2.57±2.1 c-e	7.44±1.1 c-e	9.45±1.6 bc	20.5±0.7 a	5.07±0.9 c	11.8±0.6 b
p-value	< 0.001		< 0.001		< 0.001		< 0.001		< 0.001	
F-test	***		***		***		***		***	
C.V. (%)	15.39		34.51		41.31		22.65		24.04	

* p ≤ 0.05; ** p ≤ 0.01; *** p ≤ 0.001; ns, not significantly different (F-test).

† CT = control (unamended); RS = rice straw; GN = groundnut stover; DP = dipterocarp leaf litter; and TM = tamarind leaf litter; ‡ -F = without chemical fertilizer application; +F = with chemical fertilizer application; § Means of each nutrient element followed by similar letters are not significantly different at p ≤ 0.05 (Tukey's Studentized Range Test). § Values are mean ± standard error of the mean.

In the +F, RS was significantly lower, but GN and TM had significantly higher, tissue Ca:K ratio than the control (**Table 4**). Under this chemical fertilizer management (+F), GN, DP, and RS had significantly higher tissue Mg:K ratios than the control.

Discussion

Chemical fertilizers increasing nutrient availability in residue-amended soils

Residues of low and intermediate quality only promoted corn growth when they were with chemical fertilizers (**Figure 1**). Meanwhile, the high quality residues were able to promote corn growth even when used alone. The different responses in terms of corn growth to the different soil management treatments was supported by significant interactions between residue type and chemical fertilizers, which was reflected in the dry weight of corn shoots, and nutrient concentrations and uptake (**Table 1**).

Table 4 Ratios of tissue nutrient concentrations of corn grown in coarse-textured Korat soil as affected by contrasting quality plant residues and chemical fertilizer managements, without and with chemical fertilizers.

Residues †	Tissue Ca:K ratio		Tissue Mg:K ratio		Tissue Ca+Mg:K ratio	
	-F ‡	+F	-F	+F	-F	+F
CT	2.33±0.82 ab §	0.66±0.04 c	1.33±0.32 ab	0.25±0.02 b	3.67±1.07 ab	0.90±0.05 c
RS	0.48±0.03 b	0.32±0.03 d	0.48±0.03 b	0.41±0.03 b	0.96±0.04 b	0.74±0.06 c
GN	1.97±0.05 ab	1.39±0.09 b	1.41±0.04 ab	0.97±0.06 a	3.38±0.09 ab	2.36±0.14 b
DP	1.39±0.10 ab	0.97±0.16 bc	1.71±0.09 ab	1.12±0.10 a	3.10±0.19 ab	2.10±0.26 b
TM	7.03±2.91 a	2.23±0.27 a	3.90±1.68 a	1.34±0.16 a	10.92±4.58 a	3.57±0.43 a
p-value	0.014	< 0.001	0.030	< 0.001	0.017	< 0.001
F-test	*	***	*	***	*	***
C.V. (%)	26.67	9.71	31.73	8.51	34.22	8.87

* $p \le 0.05$; ** $p \le 0.01$; *** $p \le 0.001$; ns, not significantly different (F-test).

† CT = control (unamended); RS = rice straw; GN = groundnut stover; DP = dipterocarp leaf litter; and TM = tamarind leaf litter; ‡ -F = without chemical fertilizer application; +F = with chemical fertilizer application; § Means within a ratio of tissue nutrient concentration and a chemical fertilizer management followed by similar letters are not significantly different at $p \le 0.05$ (Tukey's Studentized Range Test). The data were transformed by square root for the ANOVA test to meet the homoscedasticity, however the values shown in the table are the original means. § Values are mean ± standard error of the mean.

Increased corn growth in response to the combination of organic residues and chemical fertilizers, corresponds with the meta-analysis of Chivenge et al. (2011), who found that corn yield increased from the combined application of organic resources and chemical fertilizers. The long term application of organic residues enhanced the efficient use of chemical fertilizers through increased availability and synchronization of plant nutrients, as well as a reduction in nutrient loss in the form of gas. This enhancement of plant use efficiency of chemical fertilizers was reflected in terms of an average 54% higher corn plant yield (relative to the response to chemical fertilizer alone) under RS, 125% for GN, 44% under DP, and 54% under TM, respectively (**Figure 1**). In addition, this response was reflected in terms of higher uptakes of N, P, K, Ca, and Mg in the residue-amended treatments relative to the controls, when combined with the use of chemical fertilizers (+F) (**Table 3**). The priming effects of chemical fertilizers which induced an increase in nutrient availability of residue-derived SOM (Kuzyakov et al., 2000) may have led to the alleviation of some nutrient limitations. The combined use of organic residues and chemical fertilizers may also improve nutrient synchronization (Chivenge et al., 2011; Palm et al., 2001), and alleviation of nutrient limitation (Myers et al., 1994; Palm et al., 2001). The temporary immobilization of nutrients from chemical fertilizers by residue-derived soil organic matter (SOM) may result in an improvement of the synchrony between demand and supply of nutrients (Chivenge et al., 2011; Palm et al., 2001). Decreases in nutrient losses in the form of NH_3 and N_2O from a soil-plant system may result from the contribution of SOM (Gentile et al., 2009).

The highest corn growth under the GN treatment in combination with chemical fertilizers was likely due to the high uptakes of N and P under this treatment. Both N and P are major primary macronutrients required for synthesis of structural compounds in plant tissue. Nitrogen is required in large quantity only second to C by plants. The use of the plant test in this study has extended the knowledge of different responses of plants to the long-term application of contrasting quality residues. While TM consistently produced the highest SOM accumulation during its long-term application (Samahadthai et al., 2010; Puttaso et al., 2013; Vityakon et al., 2013), this did not translate into the highest growth of crops in this moisture optimum pot experiment. However, SOM has been shown to improve soil moisture holding capacity in soils of varying texture (Hugar et al., 2012) which is a positive attribute in unirrigated field conditions. Therefore, the results shown here have to be taken under the condition that optimum moisture levels were provided throughout.

In relation to the application of the residues alone (without chemical fertilizers), the high quality (high N, and low L and PP concentrations) of the GN brought about rapid N mineralization and high N availability (Puttaso et al., 2011). This led to a greater corn biomass under sole GN treatment than that of the unamended soil. This result is consistent with the report of Chivenge et al. (2011), who found that a greater response in terms of corn yield was obtained in response to high quality residues than residues of low quality. Amongst the low quality residues, the high C/N ratios of RS (79) and DP (75) would have brought about N immobilization. Microorganisms acquire 1 N-atom for every 20 C-atoms for their use in both body and energy maintenances (Brady and Weil, 2008). In addition, the high lignin content (246 g/kg) of DP would have resulted in great resistance to microbial decomposition. As for the intermediate quality of TM, it had a high content of polyphenols which were potentially toxic to decomposer microorganisms and therefore deterred decomposition (Swift, 1979). Furthermore, polyphenols can inhibit N mineralization through chemical stabilization with N by forming polyphenol-protein complexes (Mutabaruka et al., 2007).

Calcium-magnesium antagonism against corn potassium uptake under legume residues

The high content of Ca and Mg of legumes, i.e., GN (21.1 and 6.1 g/kg, respectively) and TM (35 and 4.5 g/kg, respectively), compared to non-legumes (i.e., RS (4.2 and 1.3 g/kg, respectively) and DP (7.9 and 3.1 g/kg, respectively), would have resulted in antagonistic effects to K uptake in corn (**Figure 2**). High K residues, i.e., GN and RS, GN, brought about higher corn K concentration than RS, but the K concentration and uptake in corn treated with GN were lower than those treated with RS, regardless of chemical fertilizers management practices (+F or -F). Similarly, with low K residues, i.e., TM and DP, TM showed lower concentrations and uptake of K in corn than DP. This indicated antagonistic effects of Ca and Mg on K, which was further supported by the use of the Ca+Mg/K ratio. It was found that there were significantly higher Ca+Mg/ K ratios in GN than RS and TM than for DP, particularly under +F

(Table 4). The norm values of Ca/K and Mg/K ratios for optimal corn growth are 0.32 and 0.14, respectively (dos Anjos Reis, 2002). Nevertheless, the antagonistic effect of Ca-Mg to K in corn under the GN amendment was not as severe as that under TM. Groundnut had a higher N content than TM. Nitrogen, which is a major nutrient, may have reduced the severity of the Ca-Mg antagonistic effects on K. This antagonism was a factor underlying the lower plant growth under TM despite its higher SOM than the GN treatment. Corn growth under the GN amendment was therefore still higher than that under the TM treatment.

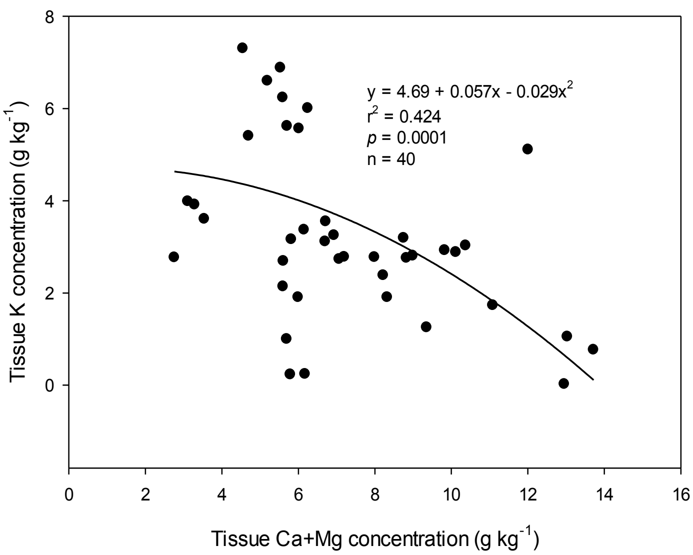

Figure 2 Relationship between sum of concentrations of Ca and Mg versus K concentration in corn shoot tissue as affected by different organic residues and chemical fertilizers management practices.

Conclusions

The results of this study clearly show the interactions between residue quality and chemical fertilizers in terms of plant/corn growth response. The combined use of organic residues and chemical fertilizers gave a significantly greater response in terms of corn plant growth, than the use of residues or chemical fertilizers alone. The combination of the use of organic residues and chemical fertilizer was reflected in increase nutrient uptake for plant growth. High quality legume residues (like groundnut) produced a higher plant yield, due to the high uptake of the two major nutrients, N and P.

High quality (N-rich) legume residues, such as groundnut, resulted in much higher plant growth with and without the addition of chemical fertilizer. A much lower plant growth response came from the legume residues of intermediate quality, such as tamarind leaf litter. Legume residues with high Ca and Mg contents, brought about Ca-Mg antagonism with K. The lower quality legumes had a more pronounced negative effect of the inhibition of on corn growth than the higher quality residue. Higher N availability from high quality legume residues was a factor that alleviated the negative effects of the Ca-Mg antagonism on K. Although the long-term (20 years) application of the intermediate quality tamarind leaf litter led to the highest SOM accumulation, this was not reflected in the highest crop/corn plant yield. However, SOM is known to improve water holding capacity. Further field testing should be conducted to determine crop performance under periodically water deficit field conditions. Plant testing, in addition to soil analysis, is therefore important in evaluating soil fertility. The results of the study also showed that crop yield is not only affected by primary macronutrients, but also by secondary macronutrients. The use of organic residues originated from N-fixing legumes is usually associated with high content of Ca, due to the symbiotic N-fixing process which requires a high Ca input. This high Ca content of the applied residues can interfere with K uptake by crops, especially those grown in highly weather K-depleted soils as shown in this study. The selection of appropriate quality organic residues for the improvement of tropical highly weathered degraded soils and crop yield, therefore, should take into account the secondary nutrient contents, in addition to major nutrient N content, of the residues.

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