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Phosphatic guano combined with steel slag as effective way for direct application of phosphatic guano to acid soil

SUWARNO (1) and GOTO Itsuo (2)

(1) Department of Soil Sciences, Faculty of Agriculture, Bogor Agricultural University, Jalan Meranti, Kampus IPB Darmaga, Bogor 16680, Indonesia
(2) Department of Applied Biology and Chemistry, Tokyo University of Agriculture, 1-1-1 Sakuragaoka, Setagaya-Ku, Tokyo 156, Japan

Phosphatic guano is solidify of sea bird excrement and solidify of bad excrement which their nitrogen have been leached, and steel slag is by-product formed in the process of steel manufacturing. Phosphate fixation and other problems in acid cause low efficiency of phosphatic guano fertilizer in acid soil. However, application of phosphatic guano combined with calcite or dolomite reduces dissolution of phosphatic guano, which in turn decreases its effectiveness. The objectives of this experiment were 1) to evaluate the combined effect of phosphatic guano and steel slag on plant growth and chemical properties of soil and 2) to study the mechanism of combined effect of phosphatic guano and steel slag.

In experiment I, phosphatic guano combined with steel slag significantly enhanced the growth of *komatsuna*, to an extent not significantly different from that of FMP with dolomite or SP with dolomite. Moreover, the response of *komatsuna* to this treatment was significant compared to combinations of phosphatic guano and dolomite. More P and B were available in soil on treatment with phosphatic guano and steel slag than phosphatic guano and dolomite. The excellent effect of phosphatic guano combined with steel slag relative to that of phosphatic guano with dolomite was attributed to the superiority of the former in supplying P and B.

In experiment II, steel slag adjusting soil pH to 5.5 combined with phosphatic guano at a PAC of 10% produced the highest yield and P uptake of *komatsuna*. Although the plant responded to either steel slag or phosphatic guano, the response to their combination decreased with the increasing amount of steel slag from that adjusting the soil pH to 5.5 - 6.5 or decreasing amount of phosphatic guano. The P availability in soil with this combination was increased as the amount of the steel slag was reduced or the amount of phosphatic guano was raised, though neither the steel slag nor phosphatic guano raised the available P in soil. In addition, steel slag enhanced soil pH, exchangeable Ca and Mg as well as available B, Mn and Fe, whereas phosphatic guano enhanced only exchangeable Ca. The best response of *komatsuna* to combination of steel slag adjusting the soil pH to 5.5 and phosphatic guano (PAC of 10%) was associated with favorable Mg and B supply from the steel slag and P supply from phosphatic guano.

In experiment III, silicate ion enhanced the solubility of phosphatic guano in 0.01 *N* KCl through the anion exchange process, while Ca ion reduced the solubility of phosphatic guano in 2% citric acid. It was suggested that the mechanism of the combined effect of steel slag and phosphatic guano as follows. Reaction of the steel slag in the soil produced Ca, Mg and other cations in addition to silicate, borate and other anions. The silicate ion exchanged for the phosphate ion of calcium phosphate mineral in phosphatic guano, thus increasing the release of phosphate from phosphatic guano, which in turn increased the concentration and the availability of P in the soil. On the other hand, Ca ion from the steel slag shifted the equilibrium between soluble Ca and phosphate ions with calcium phosphate mineral towards calcium phosphate mineral, thus reducing the phosphate release from phosphatic guano. Increasing soil pH on addition of the steel slag also reduced the solubility of calcium phosphate mineral in phosphatic guano. Moreover, the slag improved supply of Mg and B to plants.

Keywords: acid soil, phosphatic guano, steel slag

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Phosphatic guano combined with steel slag as effective way for direct application of phosphatic guano to acid soil

SUWARNO (1) and GOTO Itsuo (2)

(1) Department of Soil Sciences, Faculty of Agriculture, Bogor Agricultural University, Jalan Meranti, Kampus IPB Darmaga, Bogor 16680, Indonesia
(2) Department of Applied Biology and Chemistry, Tokyo University of Agriculture, 1-1-1 Sakuragaoka, Setagaya-Ku, Tokyo 156, Japan

Abstract

Phosphatic guano combined with steel slag significantly enhanced the growth of komatsuna, to an extent not significantly different from that of FMP with dolomite or SP with dolomite. Moreover, the response of komatsuna to these treatments were significant compared to the combination of phosphatic guano and dolomite. Phosphorus and B were more available in soil treated with phosphatic guano and steel slag than phosphatic guano and dolomite.

Phosphatic guano at a PAC of 10% combined with steel slag adjusting soil pH to 5.5 produced the highest yield and P uptake of komatsuna. Although the plant responded to either phosphatic guano or steel slag, the response to their combination decreased with decreasing the amount of phosphatic guano or increasing the amount of steel slag from that adjusting the soil pH to 5.5 - 6.5. The P availability in soil with that combination was increased as the amount of phosphatic guano was raised or the amount of the steel slag was reduced, though either the steel slag or phosphatic guano raised the available P in soil. On Andisol, phosphatic guano combined with steel slag increased soil pH, exchangeable Ca and Mg, available P and B as well as decreased exchangeable Al.

Silicate ion enhanced the solubility of P and Ca ions of phosphatic guano in 0.01 N KCl and increased Si ion retained by phosphatic guano. On the other hand, Ca ion reduced the solubility of P and Ca ions of phosphatic guano in 2% citric acid

Keywords: acid soil, phosphatic guano, steel slag

Introduction

Phosphatic guano is solidify of sea bird excrement or solidify of bad excrement which its nitrogen has been leached (Kotabe, 1997). This material has high available P (citric acid soluble P) (Table 1), so it is considerably potential to be applied directly as P fertilizer. Indonesia has many deposits of phosphatic guano spread throughout the country. Therefore, exploitation of such deposits for direct application to fulfill the local requirement of P fertilizer would enable the development of lower cost fertilizer.

One of acid soils which is important for agricultural uses in Indonesia is Andisol. These soils are used as tea or tobacco plantation and horticulture crops land because they are commonly covered under favorable climatic conditions (Tan, 1965). The most important problem in fertility of this soil order has been considered to be P supply (Amano, 1984); thus application of P fertilizer is very important in management of this soil. In comparison with other fertilizers, P fertilizer has the lowest efficiency, and normally the removal of this element by a crop does not exceed 20% of added fertilizer (Hedley *et al.*, 1990). Consequently, it is very important to develop the method for improving efficiency of P fertilizer on Andisols, particularly phosphatic guano.

Table 1 Chemical composition of phosphatic guano and steel slag.

Property	Unit	Phosphatic guano	Steel slag
Total CaO	g kg^{-1}	396.4	226.1
Total MgO	g kg^{-1}	0.7	97.6
Total P_2O_5	g kg^{-1}	301.6	4.5
Total SiO_2	g kg^{-1}	-*	160.2
Total B	mg kg^{-1}	34.1	81.8
Citric acid soluble P_2O_5	g kg^{-1}	208.1	2.1
Citric acid soluble SiO_2	g kg^{-1}	6.5	50.5
Citric acid soluble B	mg kg^{-1}	0.0	42.0

* Not analyzed

The factors limiting plant growth on Andisols should be overcome to get high efficiency of phosphatic guano on these soils. Besides P nutrient supply, limiting factors of upland crop growth on these soils correlated to soil acidity. The most effective way for overcoming problems correlated to soil acidity in Andisols, such as high levels of toxic Al and low of bases, is by liming (Shoji *et al.*, 1993). For liming such soils, steel slag is superior compared to dolomite due to its P and B contents (Suwarno and Goto, 1997). Moreover, steel slag contains high Si (Table 1), so it is hoped be able to improve the release of P from phospahtic guano.

From the above standpoints, it is important to study the combination effect of phosphatic guano and steel slag, as P fertilizer and liming material, especially for Andisols. The objectives of this experiment were: 1) to evaluate combined effects of phosphatic guano and steel slag on plant growth and chemical properties of Andisol, 2) to study mechanism of combined effect of phosphatic guano and steel slag.

Materials and Methods

Experiment 1

A pot experiment using an Andisol was carried out in the greenhouse. Each pot (Wagner's pot 5000^{-1} a) contained amount of soil equivalent to 1.40 kg of oven dried basis. Steel slag and dolomite were applied as liming materials to adjust soil pH (H_2O) to 6.5. These liming materials were combined with phosphatic guano and phosphatic guano + fritted trace elements (FTE). The phosphatic guano was applied in amounts equivalent to a phosphate adsorption coefficient (PAC) of 10% (3,000 mg P_2O_5 kg^{-1} soil). In addition, dolomite was also combined with artificial P fertilizers - fused magnesium phosphate (FMP) and super phosphate (SP) - and applied at a PAC of 5 and 10% (1,500 and 3,000 mg P_2O_5 kg^{-1} soil). The treatments were replicated three times and designed by the completely randomized design (Steel and Torrie, 1980)

Such fertilizers as 0.36 g N kg^{-1} soil of $(NH_4)_2SO_4$ and 0.36 g K_2O kg^{-1} soil of KCl were applied as basal fertilizers to all pots at one day before sowing time. Komatsuna

(*Brassica chinensis* L. cv. R*youryoku*) was planted by 20 seeds pot^{-1}, and then was thinned to 5 plants pot^{-1} at 2 weeks after sowing. This plant was harvested on 7 weeks after sowing, and the fresh weight of top was measured. Furthermore, the top part was rinsed with deionized water, dried in oven at 65°C, and then analyzed by modified closed PTFE vessel acid digestion method. After harvesting komatsuna, soil samples were taken from each pot for measurement of pH, exchangeable Ca, Mg, and Al, and available Pa and B.

Experiment 2

This experiment was conducted by the same soil and procedure as previously described in experiment I, except the following procedure. Each pot (Neubauer's pot) was filled with the amount of soil equivalent to 220 g of oven dried basis. Treatments were arranged as combination of phosphatic guano and steel slag factors. The phosphatic guano factor had 3 levels of phosphatic guano dosage: a PAC of 0, 5, and 10% (0.00, 1,450 and 2,900 mg P_2O_5 kg^{-1} soil), respectively. The steel slag factor consisted of 4 levels of steel slag dosage to adjust soil pH (H_2O) values to the initial, 5.5, 6.0, and 6.5 (0.00, 32.0, 64.0, and 128.0 g kg^{-1} soil), respectively. Moreover, all pots received 0.45 g N kg^{-1} soil of $(NH_4)_2SO_4$ and 0.45 g K_2O kg^{-1} soil of KCl as basal fertilizer at one day before sowing time. The R*youryoku* cultivar of *komatsuna* was planted by 15 seeds pot^{-1}, and then was thinned to 5 plants pot^{-1} at 10 days after sowing. This plant was harvested on 29 days after sowing.

Experiment 3

The mechanism of combined effect of phosphatic guano and steel slag was explored by evaluating the effect of silicate and Ca ions on the solubility of phosphatic guano. To evaluate effect of silicate ion on the solubility of phosphatic guano the following experiment was carried out. A series of 2 g of phosphatic guano was placed in 100 mL polyethylene bottles to which 50 mL of 0.01 N KCl containing potassium silicate ($K_2Si_4O_9$) 0, 100, 200, 300, 400, and 500 mg kg^{-1} of Si, respectively, was added. To avoid the effect of pH, the pH of those solutions was adjusted to the pH of 0.01 N KCl by HCl solution. The bottles were shaken for 1, 2, 3 and 4 hours, then their contents were filtered. The contents of P, Ca, and Si in the filtrate were measured by ICP-AES. Triplicate samples were used and the results were averaged out. Furthermore, to elucidate the effect of calcium ion on the solubility of phosphatic guano the following experiment was conducted. A series of 1g of phosphatic guano was placed in 250 mL volumetric flasks to which 150 mL of 2% citric acid solution containing $CaCl_2$ 0, 400, 800, 1200, 1600, and 2000 mg kg^{-1} of Ca, respectively, was added. The volumetric flasks were shaken for one hour at rotating shaker, their contents were filtered, and then brought to 250 ml with deionized water. The contents of P and Ca in the filtrate were measured by ICP-AES. Triplicate samples were used and the results were averaged out.

Results and Discussion

Experiment 1

As shown in Table 2, steel slag slightly improved the growth of komatsuna, whereas dolomite did not. Either phosphatic guano combined with steel slag or phosphatic guano combined with dolomite significantly enhanced the growth of the plant. The response of the plant to phosphatic guano combined with steel slag was not significantly different from that of FMP combined with dolomite or SP with dolomite. Moreover, the responses of the plant to these combinations were significantly better than that of combination of phosphatic guano and dolomite. The addition of FTE to combination of phosphatic guano and steel slag did not significantly raise the growth of this plant; however, the addition of FTE to combination of phosphatic guano and dolomite significantly raised. Both phosphatic guano combined with steel slag and phosphatic guano combined with dolomite enhanced the contents of P, K, and Ca and reduced the content of Al. In addition, the B content was enhanced with combination of phosphatic guano and steel slag, but it was reduced with combination of phosphatic guano and dolomite. The K content was greater with combination of phosphatic guano and steel slag than with combination of phosphatic guano and dolomite, while the Ca content was smaller with combination of phosphatic guano and steel slag.

Table 2 Effects of P fertilizers combined with liming materials on fresh weight and nutrient content of top part of komatsuna.

Treatment	FW of Top	Content				
		P	K	Ca	B	Al
	($g\ pot^{-1}$)	..........($g\ kg^{-1}$)..........			.....($mg\ kg^{-1}$).....	
Untreated	0.5	0.7	5.7	7.8	29.2	216.2
Dol.	0.6	0.7	5.5	23.6	14.9	221.8
Dol. + P guano	32.2	4.4	44.0	29.6	10.6	50.4
Dol. + P guano + FTE	58.2	3.7	59.5	20.9	10.0	27.3
Dol. + FMP 5%	99.2	4.9	57.0	23.5	10.4	40.8
Dol. + FMP 10%	110.1	5.3	50.4	24.0	16.3	45.4
Dol. + SP 5%	108.0	4.9	55.5	25.7	7.7	46.7
Dol. + SP 10%	113.2	4.6	53.5	25.9	13.3	40.5
S slag	16.0	2.9	56.3	24.5	41.7	47.6
S slag + P guano	103.2	3.4	58.0	19.1	36.2	30.7
S slag + P guano + FTE	105.8	3.9	69.4	17.6	37.2	36.9
Tukey's $HSD_{0.05}$	22.3	1.3	15.1	6.7	14.8	26.6
Tukey's $HSD_{0.01}$	26.1	1.5	17.6	7.8	17.3	31.0

The above results indicated that the poor growth of komatsuna on soil untreated was associated with P, K, and Ca deficiency as well as Al toxicity. Although exchangeable Al of this soil was 1.40 cmol(+) kg^{-1} (Table 3), the Al saturation was 65%; thus komatsuna plant could suffer from Al toxicity. The plant responded to steel slag, but did not respond to dolomite, indicating that the first limiting factor for growth of this plant was P supply, and the growth response of this plant to the steel slag was attributed to the supply of P. The better growth response of komatsuna to combination of phosphatic guano and steel slag seemed to be linked to P, K, and B nutrition. Available P and B in soil were higher with combination of phosphatic guano and steel slag than with combination of phosphatic guano and dolomite. The increase in K content was also higher with combination of phosphatic guano and steel slag.

Phosphatic guano combined with steel slag and phosphatic guano combined with dolomite significantly raised soil pH and exchangeable Ca and Mg as well as significantly reduced exchangeable Al (Table 3). Furthermore, phosphatic guano combined with steel slag significantly raised available P and B. On the other hand, phosphatic guano combined with dolomite only slightly raised available P, but significantly reduced available B. Soil pH and exchangeable Ca and Mg were lower with combination of phosphatic guano and steel slag than with combination of phosphatic guano and dolomite. The addition of FTE to phosphatic guano with dolomite slightly improved available P and B, and the addition of FTE to phosphatic guano with steel slag slightly improved available P.

Table 3 Effects of P fertilizers combined with liming materials on chemical properties of andisol after harvesting komatsuna.

Treatment	pH H_2O (1 : 5)	Exchangeable Ca	Mg	Al	Available P_2O_5	B
		.......(cmol(+) kg^{-1}).......			....(mg kg^{-1})....	
Untreated	5.0	0.6	0.2	1.40	29.8	0.11
Dol.	6.6	31.6	17.3	0.01	29.6	0.04
Dol. + P guano	6.8	31.7	16.9	0.01	136.9	0.04
Dol. + P guano + FTE	6.8	30.5	16.5	0.01	223.2	0.05
Dol. + FMP 5%	6.9	30.4	16.5	0.01	19.4	0.04
Dol. + FMP 10%	6.9	30.3	16.8	0.02	40.9	0.05
Dol. + SP 5%	6.6	34.1	14.6	0.01	22.3	0.08
Dol. + SP 10%	6.5	40.9	14.5	0.01	99.3	0.09
S slag	6.3	23.6	12.8	0.01	71.4	0.24
S slag + P guano	6.5	22.5	11.9	0.01	334.0	0.23
S slag + P guano + FTE	6.4	22.7	12.1	0.01	377.2	0.21
Tukey's $HSD_{0.05}$	0.1	4.0	1.6	0.05	226.1	0.07
Tukey's $HSD_{0.01}$	0.2	4.7	1.8	0.06	264.3	0.08

Experiment 2

Steel slag only slightly improved the growth of komatsuna; however, phosphatic guano and phosphatic guano combined with steel slag significantly improved the growth of this plant (Table 4). The highest yield (fresh weight of top part) and P uptake were obtained at phosphatic guano at a PAC of 10% combined with steel slag adjusting soil pH to 5.5. Although the plant responded to either phosphatic guano or steel slag, the responses to their combination decreased by decreasing the amount of phosphatic guano or by increasing the amount of steel slag from that adjusting soil pH to 5.5 - 6.5.

The result of the plant analysis indicated that responses of komatsuna to phosphatic guano, steel slag, and the combination of these materials were related to P, K, Ca, and B nutrition, and the first limiting factor for growth of this plant was the P supply (Table 4). The availability of P in the soil treated by the combination of phosphatic guano and steel slag was increased as the amount of phosphatic guano was raised or the amount of steel slag was reduced, though either phosphatic guano or steel slag raised the availability of P in the soil. In addition, phosphatic guano enhanced exchangeable Ca, whereas steel slag enhanced soil pH, exchangeable Ca and Mg, and available B (Table 5).

Table 4 Effect of phosphatic guano combined with steel slag on fresh weight and nutrient content of top part of komatsuna.

Treatment	FW of Top (g pot^{-1})	Uptake of P (mg pot^{-1})	Content P	Ca	Mg	B
			.......(g kg^{-1})......			(mg kg^{-1})
Untreated	0.7	0.1	0.7	6.9	2.2	27.7
P guano 5%	22.6	10.0	3.2	15.0	1.5	14.3
P guano 10%	24.3	14.0	3.8	16.0	1.5	9.3
S slag pH 5.5	2.5	0.3	1.0	49.5	20.6	31.0
S slag pH 5.5 + P guano 5%	28.2	14.6	3.2	17.0	6.8	23.7
S slag pH 5.5 + P guano 10%	28.4	18.5	3.9	15.7	6.7	29.6
S slag pH 6.0	2.0	0.3	1.0	48.6	22.0	57.8
S slag pH 6.0 + P guano 5%	24.8	11.3	3.2	25.6	15.8	34.9
S slag pH 6.0 + P guano 10%	28.2	16.6	3.9	20.3	9.8	32.1
S slag pH 6.5	5.7	0.7	1.0	36.4	27.7	40.8
S slag pH 6.5 + P guano 5%	18.5	5.3	2.4	33.8	26.0	37.9
S slag pH 6.5 + P guano 10%	21.8	10.7	3.7	36.2	25.2	38.7
Tukey's HSD $_{0.05}$	6.4	6.4	1.3	8.8	6.7	9.4
Tukey's HSD $_{0.01}$	7.6	7.6	1.5	10.4	7.9	11.1

Table 5 Effect of phosphatic guano combined with steel slag on chemical properties of Andisol after harvesting komatsuna.

Treatment	pH H_2O (1 : 5)	Exchangeable Ca	Exchangeable Mg	Available P_2O_5	Available B
		..(cmol(+) kg^{-1})..		....(mg kg^{-1})....	
Untreated	4.9	0.9	0.33	2.4	0.10
P guano 5%	5.0	1.8	0.34	16.7	0.16
P guano 10%	5.0	2.7	0.36	89.4	0.17
S slag pH 5.5	5.5	8.0	4.69	13.7	0.23
S slag pH 5.5 + P guano 5%	5.5	8.1	3.44	21.4	0.19
S slag pH 5.5 + P guano 10%	5.6	8.5	3.65	88.6	0.19
S slag pH 6.0	5.8	14.1	7.37	1.0	0.26
S slag pH 6.0 + P guano 5%	5.9	13.3	6.52	35.6	0.23
S slag pH 6.0 + P guano 10%	5.9	14.3	6.60	12.1	0.18
S slag pH 6.5	6.6	26.5	18.33	2.3	0.21
S slag pH 6.5 + P guano 5%	6.5	24.1	14.90	25.6	0.23
S slag pH 6.5 + P guano 10%	6.6	25.2	15.03	70.1	0.21
Tukey's HSD $_{0.05}$	0.3	4.6	5.21	32.2	0.08
Tukey's HSD $_{0.01}$	0.3	5.5	6.14	37.9	0.10

The above results indicated that the best response of Komatsuna to phosphatic guano at a PAC of 10% combined with steel slag adjusting soil pH to 5.5 was associated with favorable P supply from phosphatic guano as well as Mg and B supply from the steel slag.

Experiment 3

As shown in Table 6, although the Ca ion of phosphatic guano was soluble in 0.01N KCl, the phosphate ion of phosphatic guano was insoluble in the KCl. A part of silicate ion was retained by the phosphatic guano, and after certain amounts of silicate ion was retained, the phosphate ion of phosphatic guano became soluble. The phosphate ion was soluble when the concentration of silicate ion was greater than 200 mg kg^{-1} of Si, and the solubility of the phosphate ion was increased with increasing the concentration of silicate ion. This evidence indicated that silicate ion increased the solubility of phosphate ion of phosphatic guano through anion exchange process

Table 6 Effect of silicate ion on the solubility of p and ca ions of phosphatic guano in 0.01 N KCl and Si retained by phosphatic guano at 3 hours shaking time

No	Concentration of added Si (mg kg^{-1})	Soluble P	Soluble Ca	Retained Si
		...............(mg kg^{-1})	....	
1	0	0.0	806	0
2	100	0.0	1 003	56
3	200	0.6	1 101	153
4	300	43.8	1 257	176
5	400	38.6	1 310	181
6	500	102.9	1 501	309

Effects of Ca ion on the solubility of guano in 2% citric indicated that Ca ion reduced the solubility of Ca and P ions of phosphatic guano (Table 7). This result was similar to that obtained by Wilson and Ellis (1984) in the case of rock phosphate. In this experiment, 2,000 mg kg^{-1} of Ca ion reduced the solubility of P and Ca ions of phosphatic guano as much as 6.51 and 14.4%, respectively. This indicated that the effect of Ca ion on the solubility of P in phosphatic guano was relatively little

Table 7 Effect of calcium ion on the solubility of P and Ca Ions of phosphatic guano in 2% citric acid

No	Concentration of added Ca (mg kg^{-1})	Soluble P	Soluble Ca
		...............(g kg^{-1})	....
1	0	92.1	221.1
2	400	89.8	216.0
3	800	87.8	210.1
4	1 200	86.2	196.4
5	1 600	86.1	193.7
6	2 000	86.1	189.2

According to Krauskopf (1967) calcium phosphate minerals are insoluble in neutral and alkaline solutions; however, they are soluble in acid solution. In the case of phosphate rock, Khasawneh and Doll (1978) noted that the solubility of this material increases with decreasing pH. Moreover, Peaslee *et al.* (1962) found that the effect of H ion on the solubility of hydroxyapatite was dominant and the effect of Ca ion was only of secondary importance.

From the above results, it was suggested that the mechanism of the combined effect of phosphatic guano and steel slag are as follows. Reaction of steel slag in the soil produced Ca, Mg, and other cations in addition to silicate, borate, and other anions. The silicate ion released by steel slag exchanged for the phosphate ion of calcium phosphate mineral of phosphatic guano, so increased the release of phosphate ion from phosphatic guano, which in turn increased the availability of P in the soil. On the other hand, according to Le Chatelier's rule (Krauskopf, 1967), the Ca ion released by steel slag shifted the equilibrium between soluble Ca and phosphate ions with calcium phosphate mineral of phosphatic guano toward calcium phosphate mineral; thus it reduced the release of phosphate ion from phosphatic guano. Increasing soil pH after addition of the steel slag also reduced the solubility of calcium phosphate mineral of phosphatic guano. Besides its effect on the phosphate release from phosphatic guano, the steel slag improved the supply of Mg and B to plants.

Conclusions

The effect of phosphatic guano combined with steel slag on the yield of Komatsuna was not significantly different from that of FMP combined with dolomite or SP with dolomite, but significantly better than that of phosphatic guano with dolomite. The excellent effect of phosphatic guano combined with steel slag relative to that of phosphatic guano with dolomite was attributed to the superiority of the former in supplying P and B. The best effect of phosphatic guano combined with steel slag was obtained at phosphatic guano at a PAC of 10% with steel slag adjusting soil pH (H_2O) to 5.5. This was associated with favorable P supply from phosphatic guano as well as Mg and B supply from the steel slag. On Andisol, phosphatic guano combined with steel slag increased soil pH, exchangeable Ca and Mg, available P and B as well as decreased exchangeable Al.

The mechanism of the combined effect of phosphatic guano and steel slag was as follow. The silicate ion resulted by steel slag exchanged for the phosphate ion of phosphatic guano, so increased the release of phosphate ion from phosphatic guano, which in turn increased the availability of P in the soil. However, Ca ion from the steel slag reduced the release of phosphate ion from phosphatic guano. Increasing soil pH after the addition of the steel slag also reduced the solubility of phosphatic guano. Phosphatic guano combined with steel slag is an effective way for direct application of this P fertilizer to Andisols.

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