Fate of manure phosphorus in a weathered sandy clay loam soil amended with three animal manures

J.O. Azeez , W. Van Averbeke

Department of Crop Sciences, Tshwane University of Technology, Private Bag X680, Pretoria 0001, South Africa

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a b s t r a c t

Laboratory incubation was conducted for 120 days to study the fate of phosphorus in poultry (PM), cattle (CM) and goat manures (GM). Phosphorus mineralized from manure was dependent on total P, Al and Fe content. Manures improved P availability in the order: PM > CM > GM; however, the highest amount of P was fixed or immobilized between 10 and 70 days of incubating with CM and GM. Fixation and immobilization of mineralized P from poultry manure was negligible probably due to the high total P and the low amount of Al and Fe. Generally, manure application reduced the ability of the soil to fix P. More than 90% of the manure P was either immobilized or fixed by the soil. The relationship between the amount of P released and time was cubic. Improvement of the C:P ratio of CM and GM would be an option to enhance their agronomic use as fertilizer P source.

1. Introduction

The application of manures to soil for the improvement of fertility and crops growth has always been done using manure N as the indicator nutrient. Rate and timing of manure application is mostly based on N content, but this approach has led to over-fertilization, particularly with nutrients like phosphorus (Edmeades, 2003). The nutrient content of most animal manures is not what is required by crops, and phosphorus pollution of soil and ground water following application of animal wastes has been observed (Evanylo et al., 2008). Edmeades (2003) reported excessive accumulation of P as a result of long term use of manure in the Rothamsted trials. However, this type of pollution occurred in a temperate region where the soils are very low or lacking in sesquioxides and kaolinitic clays. These clays have been reported to fix phosphorus in soils at low soil pH, while calcium oxides fix P at high soil pH (Tisdale et al., 1993). These problems have made some authors advocate the use of P as indicator nutrient for manure rates and timing of application (Whalen and Chang, 2001). In tropical countries, the majority of soils are high in oxide clays and consequently, P fixation is a major soil fertility problem (Siddique and Robinson, 2003). Except for areas with direct dumping of manures, over-fertilization of soil with P from manures seldom occurs in most African countries.

It is difficult to predict the availability of manure nutrients to crops due to several turn-over processes and losses (Sorenson, 2001), but is important to understand the phosphate chemistry in manure-amended soil in order to predict the net mineralization of manure P. Particularly, since transformations in manure are usually complex outcomes of biotic and abiotic factors (Qiu et al., 2008). Adsorption and dissolution are some of the abiotic factors that may control nutrient transfer between non-living pools and soluble forms while processes mediated by microbes are the biotic factors that change organic P into plant available forms.

Despite the importance of P in plant nutrition, most studies on manure, with the exception of two recent studies in South Africa (Gichangi and Mnkeni, 2009; Gichangi et al., 2009), have focused on its effect on crop production (Mugwira et al., 2002; Eghball et al., 2004; McAndrews et al., 2006) or mineralization of nitrogen and its forms (Abbasi et al., 2007). Few studies have addressed the effect on soil P (Evanylo et al., 2008; Edmeades, 2003). Hence, there is a need to document the changes in soil P when manure is applied. Nutrient imbalances in manures occasioned by differences in animal types, management systems, sex and age of animals (Azeez et al., 2009), have significant effects on nutrient release patterns and the subsequent microbial interactions with the manures. Providing information on the fate of P will help in providing a basis for management decisions on manure use. Accordingly, the objectives of this study were to evaluate patterns of phosphorus mineralization in an incubated soil to which three animal manures were applied and to estimate the kinetics of P release from the manures.

2. Methods

2.1. Soil and manure analyses

Yellowish-red, low-fertility ultisol (Azeez and Van Averbeke, 2009) was air-dried and sifted with a 2-mm mesh sieve. The bulk

of the soil was stored in the laboratory while a subsample was analyzed for pH in a 1:2.5 (soil:water) and KCl solution (1:1) (soil:1 N KCl solution) using a glass electrode pH meter. Available phosphorus was extracted using Olsen's extractant (Watanabe and Olsen, 1965), while the P in the extract was determined spectrophotometrically (Cater, 1993). Total Nitrogen in the soil was digested and analyzed using the Kjedahl method (Kaira and Maynard, 1991). Na, Mg, Ca, and K were extracted with 1 N ammonium acetate. Na and K in the extract were determined by flame photometry, Ca and Mg by Atomic Absorption spectrometer (AAS). The particular size distribution of the soil was determined by the hydrometer method (Cater, 1993). The manure (cattle, poultry and goat) samples were from the same locations as described by Azeez et al. (2009). The manures were air-dried, homogenized by hammer milling to a particle size of less than 1.5 mm, and extracted with water or digesting with HNO_3 and H_2SO_4 for macro and micro nutrients by standard procedures (Kaira and Maynard, 1991; Cater, 1993).

2.2. Laboratory incubation

Triplicate samples of 200 g of finely ground, air-dried (after sieving through 2-mm mesh) soil weighed were transferred into 400-mL plastic containers, weighed, and mixed with soil. The application rate was equivalent to a recommended rate of 120 kg N ha^{-1} based on the assumption that the mass of the furrow slice was 2240 t ha^{-1} (Van Averbeke et al., 2007). The equivalent application rates of phosphorus were 29.64, 49.39, and 24.08 kg ha^{-1}, for cattle (CM), poultry (PM) and goat (GM) manure, respectively. Soil without manure was used as control. The samples were incubated in a dark cupboard at 23 oC for 120 days. Occasionally (once weekly), the moisture content was adjusted to field capacity (14.6%, w/w) by adding distilled water. A total of 108 experimental units were used in a factorial trial with a completely randomized design. The factors were the different animal manure types and the incubation periods. During this process, care was taken not to disturb the soil either through stirring or shaking. Samples of the four treatments incubated for different timings were analyzed for P extractable with 0.5 M sodium bicarbonate (Watanabe and Olsen, 1965). P content of the soil and of soil plus manure samples at day 0 were determined immediately after incorporation of the manures. Subsequently, mineralization of P was assessed by destructive sampling. Triplicate samples were removed from different treatments randomly from the incubator at days 10, 20, 30, 40, 55, 70, 90, and 120. Extracts were prepared, filtered through Whatman's No. 40 filter paper, ascorbic acid (1%) and molybdate reagent (Cater, 1993) were added, and the P content was determined using a WPA® 92 , S800 diode array spectrophotometer at a wavelength of 720 nm.

A total of 108 experimental units were used for the incubation trial. The experiment was a factorial trial in completely randomized design. The factors were the different animal manure types and the incubation periods. During this process, care was taken not to disturb the soil either through stirring or shaking. Samples of all four treatments incubated for different timings were analyzed for 0.5 M sodium-bicarbonate extractable phosphorus (Watanabe and Olsen, 1965). Due to the ease of preparation and its adaptability to wide range of tropical soils, $NaHCO_3$ was used as the extractant. The choice of so initial P content of the soil only and soil + manure samples at day 0 were determined in same reagent added directly to the soil immediately after incorporation of each manure source, and the P content determined after filtration. The colour of the samples was development done before analysis on a spectrophotometer by adding ascorbic acid and molybdate reagents. Subsequently, mineralization of P was assessed routinely by destructive sampling. This was achieved by removing triplicate samples from different treatments randomly from the incubator at different incubation periods (i.e., 10, 20, 30, 40, 55, 70, 90, and 120 days). After the extraction process, the aliquots were filtered through Whatman's No. 40 filter paper. The P content of the filtrates was determined using the WPA®, S800 diode array spectrophotometer at a wavelength of 720 nm.

2.3. Calculations

Manure P mineralized (P_{org}) at each sampling time (t) was calculated according to Griffin et al. (2005), as reported by Abbasi et al. (2007)

$$P_{org}\,(\mathrm{mg\,kg^{-1}\,soil}) = \{[Pi]_t - [P_i]_{t=0}\}_{manure} - \{[Pi]_t - [Pi]_{t=0}\}_{unamended};$$

where P_i is the phosphorus concentration at time t. The percentage of total P released from an applied P source at time t was calculated as: $(\%\,P_{rel})_{P\ source} = [(P_{rel})_{(P\ source)}/P_{0(P\ source)}] \times 100$, where P_0 is the total P in manure sources. The P release kinetics was also estimated by plotting a graph of P release against the time of incubation, line of best fit, with the highest coefficient of determination (R^2) was adjudged as best that described the P release.

2.4. Statistical analysis

All data were statistically analyzed by factorial analysis of variance (ANOVA) using the software package SAS (1999). Significant treatments means were separated using the least significant differences (LSD) value at 5% level of probability.

3. Results and discussion

3.1. Soil and manure characteristics

The soil is a sandy clay loam of low fertility status and had a pH in water of 5.9 and of 4.9 in KCl. It contained 1.4 mg P kg^{-1} (Olsen extraction) in its natural state. The soil N, P and K values were very low and the soil was thus suitable for the mineralization trials (Van Averbeke et al., 2007). As previously reported (Azeez and Van Averbeke, 2009), PM had a significantly higher total carbon, water and sodium-bicarbonate extractable P content than both CM and GM, however, GM had significantly higher total C and water–P than CM. There was no significant difference in the aluminum and iron contents of GM and CM. The Al and Fe contents of both manures were significantly higher than those of PM. The other properties of the manures are shown in Fig. 1. The total P and total N in poultry manure was significantly higher than that of cattle and goat manure. Accordingly, C:P and N:P ratios of the manures were in the order of GM > CM > PM. PM is thus richer than the other two manures, and this observation confirms the animal source-dependent qualities of manure (Chadwick et al., 2000). The higher C:P and C:N ratio observed in GM and CM relative to PM implies that poultry manure is expected to mineralize faster than cattle manure and goat manure (Chadwick et al., 2000; Trinsoutrot et al., 2000; Qiu et al., 2008). Manures with high C:P and C:N ratios are also reported to retard plant growth by reducing plant availability of soil N (Azam, 2002). Possible immobilization of P is also connected with high C: P ratios (Hobbie and Vitousek, 2000). Aluminum and Fe in goat and cattle manures are expected to mineralize and form part of the soil's Al and Fe pool, possibly due to the high solubility of the manure components. This will consequently reduce the P availability in the soil. Oxides of Al and Fe have been reported to fix P at low soil pH (Tisdale et al., 1993). With the acidic nature of the soil under study, P fixation by the soil might be enhanced by the addition of the manures, particularly in GM and CM because of their Al and Fe contents. This problem is

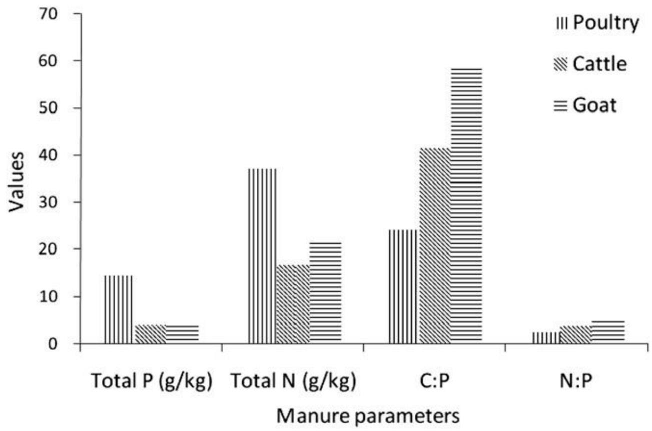

Fig. 1. Some characteristics of the manures used for the incubation experiment.

likely to be aggravated with the lower total P content of CM and GM and the corresponding high Al and Fe values. Generally, PM was superior to CM and GM in quality; this might be a reflection of the management systems adopted in raising the animals. Poultry manure was from an intensively managed system where all the nutritional needs of the birds were met. In contrast, the kraal manure of cattle and goat was from animals kept in a semi-intensive system where the animals scavenged for feed and return at night to their shelter beds. Hence, concerns about fixation and microbial immobilization of applied P is will be higher in GM, then CM and least in PM.

3.2. Net mineralization/fixation/immobilization of organic phosphorus

The time dependence of P mineralization in soil across manures types is shown in Table 1. There was a gradual, but not significantly different ($p > 0.05$) increase in soil P (relative to day 0) up to day 20. A significantly higher soil P was recorded at day 40 and values decreased significantly afterwards. The magnitude of the decrease was 11%, 14%, 61% and 92%, for 55, 70, 90 and 120 days after incubation, respectively. Mineralization of manure P increased with time and reached its maximum at 40 days. The subsequent decrease in P might be due to fixation of the mineralized P by Al and Fe oxides or immobilization by the soil microbes. The data in Table 1 show that all the manure types significantly improved soil P over the control in the order of PM > CM > GM and that most of the P released by the manures was not fixed by soil colloids. This observation was more pronounced for the PM- than the GM-treated soil. Hence, the addition of manure to soil improves P availability. This improvement is perhaps due to the sealing of P sorption sites by the organic ligands in the manures and the possibility that the effect of manure on soil P availability superseded that from colloidal fixation. Similar results were reported by Agbenin and Igbokwe (2006) and Sibanda and Young (1986). The effect of manure application on the P release showed varied trend among the manure types and the control (Fig. 2). The value of soil P in the control soil was only positive at days 20, 40 and 55. There was a negative soil P balance at 10, 30, 70, 90 and 120 days. Cattle and goat manure-treated soil showed similar trends. The soil P was either fixed or immobilized in these treatments. The magnitude of this fixation/immobilization was highest at 20 days. For the other time points, similar values were recorded for the two manure treatments. The higher negative values in soil P for both manures compared with the control soil indicated that the effect of both colloidal fixation and immobilization was higher between days 10 and 70. Fixation of soil P was more prominent at days 90 and 120. The initial C:P ratios of the manures could have been responsible for the fixation of P by the manures' microbes, this P problem could also be aggravated by fixation of P by colloids, and this is expected because of the soil high Fe and Al content. The two manures could have also contributed to the soil's Al and Fe pool because of the solubility of manure content. The confounding effect of both factors might have peaked after 70 days. Subsequently, the microorganism could be assumed to have died or stopped growing or metabolizing, hence making the effect of the fixation higher at 90 and 120 days. The trend observed could have also reflected the manures' initial P contents. Poultry manure-treated soil had a positive P balance for the duration of the incubation; however, the fluctuations in the soil P over time were constant up to 55 days. A small increase was observed at 70 and 90 days and a significantly higher P value was recorded after 120 days.

The positive P balance in PM-treated soil could have been the result of the higher P levels in poultry which could have masked the effect of colloidal fixation of mineralized P. Poultry manure's C:P, C:N values also did not favor immobilization of P by microbes. The average values for soil P content during the incubation period revealed that only the P in PM was mineralized while that from GM and CM were immobilized by soil microbes (Fig. 3) because of their high C:P ratios. The control soil had a higher magnitude of fixation/

Table 1
Effect of incubation days and manure types on the mineralization of phosphorus in soil incubated with or without animal manures.

Incubation days	Phosphorus (mg/kg)
0	7.25 (0.21)[a]
10	7.40 (0.36)
20	7.27 (0.35)
30	7.13 (0.28)
40	7.92 (0.21)
55	7.04 (0.21)
70	6.85 (0.24)
90	3.06 (0.27)
120	0.67 (0.41)
lsd ($p < 0.05$)	0.45
Manure types	
Control	5.20 (0.49)[b]
Poultry	7.15 (0.39)
Cattle	6.14 (0.50)
Goat	5.77 (0.51)
lsd ($p < 0.05$)	0.3

[a] Values (across manure types) in parenthesis are standard error of the means (SEM), n = 12.
[b] Values (120 days of incubation) in parenthesis are standard error of the means (SEM), n = 27.

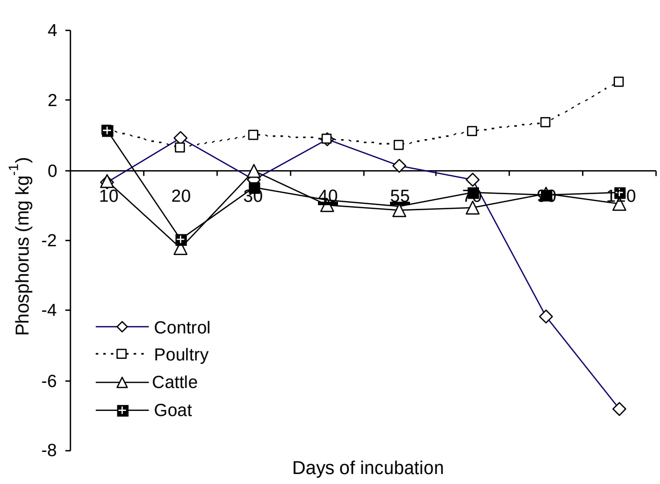

Fig. 2. Effect of manure types on phosphorus release from manures.

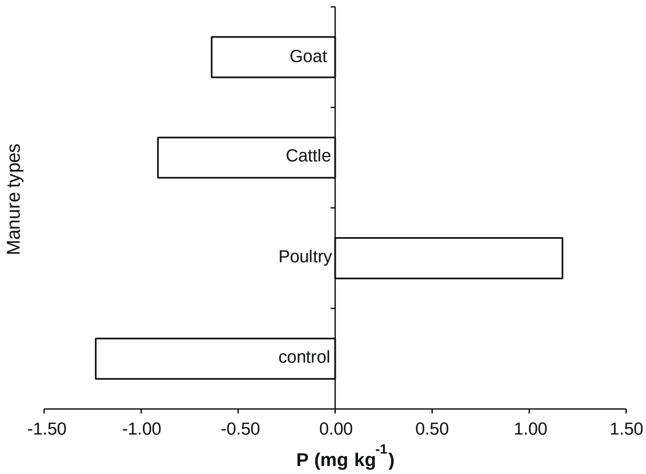

Fig. 3. Effect of manure types on phosphorus mineralization and immobilization (average across 120 days of incubation).

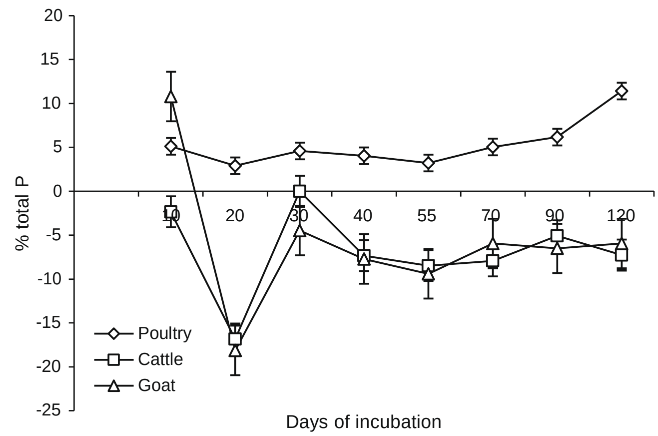

Fig. 4. Percent total P mineralized by manures types (bars = standard error bars).

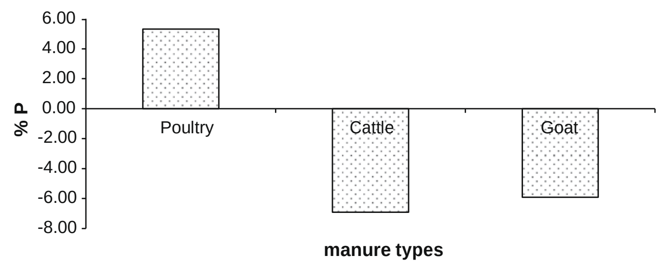

Fig. 5. Percent total N mineralized (average across 120 days of incubation) (bars = standard error bars).

immobilization compared to either GM or CM. This result shows that the two manures reduced P fixation in the soil alone (control). The ability of the manures to reduce P fixation was highest in poultry manure, followed by goat manure and least in cattle manure. This effect could have been due to the blockage of adsorption sites by sorbed humic acid from the manures (Sibanda and Young, 1986). Hence, PM perhaps has more ligands released from its oxidation of organic molecules and consequently increased its competitive ability for sorption sites (Agbenin and Igbokwe, 2006). The contribution of manure to soil Al and Fe content was also highest in cattle manure (11.25 g kg^{-1}, Fe; 10.85 g kg^{-1} Al) followed by goat manure (10.40 g kg^{-1}, Fe; 10.55 g kg^{-1} Al) and very low in PM (1.86 g kg^{-1}, Fe; 1.09 g kg^{-1} Al). Such values could have also contributed to the observed trends. The majority of P in manure has been reported to be in inorganic form (He et al., 2004; Kashem et al., 2004). Ebeling et al. (2003) have also reported the formation of insoluble P compounds by high amounts of Al and Fe in biosolids. To accurately estimate the P release by the manures, the measured soil P content was expressed as a percentage of the manure P applied (Fig. 4). GM and CM behaved similar in terms of the magnitude of P release with time; however, the proportion of P released was highest in goat manure treatments after just 10 days of incubation. The highest proportion of the applied P was immobilized/fixed at 20 days. The percent P released (relative to total manure P) for both manures were very close for the duration of the incubation. In contrast, PM treatment resulted in mineralization of about 5% of the total P at day 10 and of 2.9% just 10 days thereafter (20 days of incubation). The proportion of P mineralized was almost constant between 30 and 70 days. The highest (11%) amount of P was mineralized after 120 days 198 of incubation. Fig. 5 shows that for the duration of the incubation (120 days), only 5.31% of the total poultry manure P could be accounted for by $NaHCO_3$ extraction. About 7% and 6% of the P in cattle and goat manure were immobilized and/or fixed, respectively. Therefore, cattle and goat manure mineralized more P than PM, however, all the P released was fixed or immobilized. Hence, improvement of the C:P ratios of these manures could be one of the management options to enhance their agronomic use as fertilizer P source.

3.3. Nitrogen release kinetics

The coefficient of determination (R^2) was used as the criterion for fit to describe the kinetics of the P release (Table 2). Only soil alone and poultry manure-treated soil could be described with 93% and 80%, respectively, of the variations in the data captured by the model. The predictive power of the model was about 40% for goat manure-treated soil while the value was as low as 13% for the cattle manure treatment. Generally, the relationship between P release and time was not linear, but polynomial to the power of three for all manure treatments and square for soil alone (control). The slope of the graphs was very gentle, indicating that the release of P over time was almost constant. The high value observed in soil alone was due to the sharp increase in P recorded at days 90 and 120. The low R^2 values in the cattle and goat manure treatments could probably be due to the fluctuating P release

Table 2
Estimated parameters from equations describing phosphorus release in soil and manures.

	Parameters					
	Y	X^3	X^2	X	Constant	R^2
Soil only	P amount	–	−0.001	0.0634	−0.5268	0.93
Soil and poultry manure	P amount	0.0006	−0.0005	0.028	0.338	0.80
Soil and cattle manure	P amount	−0.00006	0.0011	−0.0639	0.114	0.13
Soil and goat manure	P amount	−0.50	0.0021	−0.1305	1.3362	0.38

Y = amount of P released (mg kg^{-1}), X = time (days) of incubation.

patterns caused by mineralization; immobilization and perhaps soil fixation could have distorted the data (Dang et al., 1994).

4. Conclusion

Manures improved P availability in the order: PM > CM > GM. Generally, manure application reduced the ability of the soil to fix P. Improvement of the C:P ratio of CM and GM would be an option to enhance their agronomic use as fertilizer P source. The relationship between the amount of P release and time was cubic.

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