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SORPTION OF PHOSPHORUS IN SOILS IN THE SEMI DECIDUOUS FOREST ZONE OF GHANA

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ABSTRACT

The study conducted investigated phosphorus (P) sorption at varying depths of the soil column and the results were interpreted with reference to some physico-chemical properties of the soils. The samples were taken from soil depth of 0-30 cm from two land use systems (a cocoa plantation and an arable land under the cultivation of cowpea). The soil samples were packed into transparent polyvinyl chloride (PVC) cylinders and the phosphorus solutions applied at 69 ppm. After, 72 hours, the soil samples in the PVC cylinders were carefully taken and sectioned at 5 cm interval, that is, 0-5, 5-10 and 10-15 cm. Soil separates were air-dried and the P content determined. The vertical distribution of phosphorus through the soil column decreased significantly with depths in soils under both land-use systems. The soil under the arable land sorbed more P than the cocoa plantation soils at soil depths of 0-5 and 5-10 cm. The contrary occurred at the soil depth of 10-15 cm where more P was sorbed by soil under the cocoa plantation. The study showed that soil organic matter content, hydraulic conductivity and water flux density could hinder the sorption capacity of soils. Also, the impact of aluminium and iron to fix phosphorus in acidic soils is hindered by the above soil properties. The differences observed in the P sorption capacities of the soils suggested that, the use of blanket phosphate fertilizer recommendations may not be a good strategy as it may lead to under application or over application of P in some areas with the consequence of compromising crop yields or freshwater quality.

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1. INTRODUCTION

When phosphorus (P) fertilizers are applied to the soil, they are dissolved by soil water. Various reactions occur between the phosphate ions (H_2PO_4^- and HPO_4^{2-}) and soil constituents which sorb P from the solution phase and render it less variable [1]. This phenomenon is termed P fixation or sorption. Phosphate ions are chemically unstable in soil solution, and readily reacts largely with aluminium (Al), iron (Fe) and calcium (Ca) to form less soluble and more stable compounds [2, 3]. Sorption affects the ability of most soils to release phosphorus (P) into soil solution for plant uptake. Additions of fertilizers are therefore needed to increase the labile P in soil solution.

Soils differ in their ability to hold P although P sorption is high in all the soils [1, 4, 5]. [6] Found out that inorganic phosphate (PO_4^{3-}) was more strongly sorbed than dissolved organic phosphorus (DOP). The authors subsequently suggested that DOP was thus more susceptible to leaching than PO_4^{3-} . Comparing triple

superphosphate (TSP) to Gafsa phosphate rock (GPR), [7] reported that more P (threefold) leached from TSP than GPR treatments.

Studies on the P sorption behaviour of soils have shown that they vary with soil depths. Tilahum [8] reported that available P was higher in the subsoils than the topsoils. Borggaard et al [9] posited that enrichment of Al and Fe in the B horizon of acidic soils of Podzols makes them more efficient in sorbing P. This corroborates the findings of Vaananen et al. [10] that there was a sharp distinction between horizon O and E which showed lower P retention than horizon B1 and B2. Vaananen et al. [10] further suggested that the low P sorption in the O and E horizon would make them more prone to P leaching as compared to the B horizon. Nonetheless, Tischner [11] observed that, beyond the 30 cm soil depth, the concentration of soluble P decreased with increasing depth.

Phosphorus sorption is widely linked to the pH of the soil which in turn affects P association with aluminium, iron and calcium. But other soil properties such water flux density, hydraulic conductivity and, clay and soil organic matter content could also play a great role in determining P sorption in soils. Hardy et al. [12] reported that clay and organic matter are the most chemically active soil solids and are the major soil components to which most chemicals sorb. Investigating P sorption with reference to the physico-chemical properties of soils at varying depths could give a better understanding of P dynamics in soils.

The hypothesis of the study was that, Fe, Al and Ca play the major role in influencing P sorption in accordance to soil depth. Based on the hypothesis, the objective of the study was to investigate phosphorus sorption at varying depths of soil column and interpret the results with reference to some physical and chemical properties of the soil.

2. MATERIALS AND METHODS

2.1. Experimental site and soil sampling

The study was carried out at the Soil Science Laboratory of the Department of Crop and Soil Sciences, Kwame Nkrumah University of Science and Technology (KNUST). Soil samples were taken from the Plantation Section of the same Department from two land use systems; a cocoa plantation and an arable land under cultivation of cowpea. Geographically, the experimental area stretched from latitudes 6° 40' North and longitude 1° 33' West. Soil samples were randomly taken at soil depth of 0-30 cm from the two land use systems. The soil samples were air-dried and passed through a 2 mm sieve. The soil particles that passed through the 2 mm sieve were used for the physical and chemical analysis.

2.2. Soil sampling and physico-chemical analysis

The particle size distribution of the soils was determined using the hydrometer method [13] whilst soil bulk density was determined by the metal core sampler method [14]. The total porosity of soil was calculated using the formula:

$$f = 1 - \frac{\rho_b}{\rho_s} \quad (1)$$

Where:

f = total porosity

ρ_b = bulk density and

ρ_s = particle size density (2.65 g cm⁻³).

Saturated soil hydraulic conductivity was determined using the modified falling head method [15]. The water flux density of the soils was determined as follows:

$$\text{Water flux density} = \frac{Q}{t \times A} \quad (2)$$

Where:

Q = Quantity of water per unit time, t and

A = area of soil column

Soil pH was determined using a standard pH meter in a soil: water ratio of 1: 2.5. Soil organic carbon (SOC) was determined by the modified Walkley and Black dichromate digestion method [16]. Available phosphorus was determined using the Bray P1 method [17]. Exchangeable Ca, Mg, K and Na were

determined after extracting the soil samples by ammonium acetate (1N NH_4OAc) at pH 7.0. Exchangeable Ca and Mg in the extracts were analysed using Buck scientific atomic absorption spectrophotometer, while Na and K were analysed by Gallenkamp flame photometer [18, 19]. Iron was determined using Diethylenetriamine penta acetic acid (DTPA) extraction method as described by [20] whilst aluminium was determined using the spectrophotometric method [21].

2.3. Experimental design and treatments

The treatments considered were soils of depth 0-5, 5-10 and 10-15 cm. Phosphorus sorption in relation to the varying depths of soils within each field was arranged in CRD. In all, 9 experimental units were considered in each land use system. T-test at 5% confidence limit was used in separating the means of P sorption between the land use systems.

2.4. Experimental setup and column preparation

The experiment was conducted using improvised transparent polyvinyl chloride (PVC) cylinders. The cylinders were 45 cm long with internal diameters of 10 cm. The PVC cylinders were attached to a backboard. The PVC cylinders were removable from the backboard to facilitate filling and cleaning. A tube was fixed to the base of the cylinders to allow effluents flow into beakers placed underneath. White calico of diameter 10 cm was cut to fit the base of the cylinder. Soil aggregates of diameters 1-2 mm, 2-4 mm and 4-8 mm were also prepared. Both the calicos and the soil aggregates were prepared to filter dirt from the outflow. Also, interception of flow without the calico and the packed aggregates would have caused more P solutions to flow through the basal collecting tubes.

The column was prepared layer after layer bottom up as follows: the calico was placed at the base of the PVC cylinder and the three soil aggregates packed in succession to the 5 cm mark of the PVC cylinder in the following order: aggregates of diameter 4-8 mm to 0-2 cm layer of the cylinder, 2-4 mm to 2-4 cm and 1-2 mm to 4-5 cm mark. Thereafter, the soil samples were packed to fill the 5-20 cm layer of the PVC cylinder at soil density of 1.3 g cm^{-3} (height of soil was 15 cm). White calico was again placed on top of the soil sample and an aluminium mesh fixed on it to hold it firm in place to prevent splashing of soil particles whilst applying solutions to the soil column. That is, to avoid pore clogging.

The soil columns were saturated slowly from the bottom by immersing them in buckets containing distilled water before starting the transport experiments. This was to ensure uniform wetness and to expel air out. Before applying the solutions to the soil columns, the plastic tubes from which the effluents flowed were corked to prevent outflow. Phosphorus solutions at 69 ppm were then applied to the soil columns at a volume of 1571 cm^3 . The soil columns were allowed to thoroughly drain for 72 hours. Soil samples in the PVC cylinders were then carefully taken out as the soil cores took the shape of the PVC cylinders. They were then divided at 5 cm interval, that is, 0-5, 5-10 and 10-15 cm. Soil separates were air-dried and the P determined using the Bray P1 method [17].

2.5. Statistical analysis

The data collected on the various parameters were subjected to analysis of variance using GenStat statistical package (12th Edition). Means were separated using least significant difference (Lsd) at 5% probability level. Each treatment was replicated three times. Differences between the physico-chemical properties of the two sites were analysed using a two sided T-test at a confidence limit of 95%.

3. RESULTS AND DISCUSSIONS

3.1. Physico-chemical properties of the soils

The chemical and physical properties of the soils from the test sites are presented in Tables 1 and 2. The textural class of soil under the arable land and cocoa plantation was loamy sand. Using the Landon [22] guidelines for soil physical and chemical interpretation, the pH values of the soil under the arable land was strongly acidic whereas that under the cocoa plantation was moderately acidic but statistically, no difference in pH was observed between the two systems. Phosphorus in soil solution is highly dependent on pH and it reacts with iron (Fe) and aluminium (Al) to form insoluble Fe and Al phosphates in acid soils and with calcium (Ca) to form insoluble Ca phosphates in alkaline soils [3, 23]. It was therefore expected that P fixation (sorption) in both land use systems would be linked more to Fe and Al reactions with P but this was not the case in this study. The available phosphorus content of both soils were low but statistically, it was higher ($p < 0.05$) in soil under the arable land than in the cocoa plantation. The field porosity of both cocoa

plantation and arable land were < 0.50 . Soil under the arable land contained lower ($p < 0.01$) amount of organic carbon as compared to soils under the cocoa plantation. The low SOC observed under the arable land could be due to inadequate inputs of organic residues to this system. This corroborates the finding of Grace et al. [24]. Crop residues application as surface mulch play an important role in the maintenance of soil organic carbon levels and productivity through increased recycling of nutrients and minerals, increasing fertilizer use efficiency, improving soil chemical and physical properties and, decreasing soil erosion [25]. Large amount of crop residues deposited on the surface of the cocoa plantation could have accounted for the higher SOC observed.

The exchangeable cations (except K^+) were higher in the cocoa plantation than in the arable land. According to Tilahun [8], high exchangeable cations are an indication of the capacity of soils to retain nutrients against leaching. Therefore, the higher exchangeable cations in soils under the cocoa plantation suggested greater capability of these soils to retain nutrients against leaching. Again, this was not the case in regards to P sorption in this study.

Water flux density, hydraulic conductivity, iron and aluminium concentrations were significantly ($p < 0.01$) higher in soils under the cocoa plantation than soils under arable land cultivation. The time taken for the P solution to leach out of the soil columns took (transit time) 30 minutes under the cocoa plantation and 105 minutes under the arable land. This was mainly attributed to the variations in the SOC content between the land use systems. Better aggregation of soil is linked to soil organic matter and this improves water infiltration and thus reduces runoff [26, 27]. Organic matter content of soils also greatly affects the hydraulic properties [28]. Therefore, the higher organic carbon content of the soil under the cocoa plantation improved its hydraulic conductivity which further increased the water flux density.

Table 1 Physical properties of the soils

Soil property	Arable land	Cocoa plantation
Sand (%)	80.76	84.76
Silt (%)	9.72	5.05
Clay (%)	9.52	10.19
Bulk density ($g\ cm^{-3}$)	1.56	1.39
Porosity	0.41	0.48
Textural class	Loamy sand	Loamy sand

Table 2 Some physico-chemical properties of the soils

Soil property	Arable land	Cocoa plantation	p (0.05)	SE
Organic carbon (%)	1.11	1.52	0.01	0.060
Available P (ppm)	3.08	0.36	0.05	0.810
Ca^+ ($cmol\ kg^{-1}$)	2.50	6.07	0.01	0.680
Mg^+ ($cmol\ kg^{-1}$)	1.80	2.40	0.19	0.380
K^+ ($cmol\ kg^{-1}$)	0.15	0.10	0.01	0.003
Na^+ ($cmol\ kg^{-1}$)	0.26	0.32	0.01	0.006
Fe (ppm)	5.61	11.69	0.01	0.120
Al ($cmol\ kg^{-1}$)	0.80	3.24	0.01	0.080
pH (1: 2.5 soil: H_2O)	5.11	5.55	0.07	0.194
Water flux density ($m\ s^{-1}$)	0.003	0.01	0.01	4×10^{-5}
Saturated Hydraulic conductivity ($cm\ s^{-1}$)	0.002	0.01	0.01	5×10^{-5}

SE: standard error of mean, p: probability

3.2. Sorption of phosphorus in terms of the vertical distribution of the soil

Table 17 showed how the various soils depths (0-5, 5-10 and 10-15 cm) affected P sorption in soils under the arable land and cocoa plantation. With regards to P sorption in accordance to soil depths, the vertical distribution of P through the soil column decreased significantly ($p < 0.01$) with soil depths in soils under both land use systems. In relation to soils under the cocoa plantation, no significant difference was observed in the P sorbed between soil depths of 0-5 and 5-10 cm. However, significant differences were recorded between soil depth of 0-5 and 10-15 cm and, 5-10 and 10-15. Major differences in P sorption were detected in soil depths under the arable land.

According to Borling [29], P leaching appeared to depend more on inherent soil characteristics, such as water transport mechanisms and P sorption capacity in the profile. The phosphorus solution percolating

through the soil column steadily mixes with and slowly displaces the water initially present in the soil pores. Chemical reactions occurred between the P and soil constituents which caused the P from the soil solution phase to be sorbed to soil constituents [1-3]. But the contact time of P ions (orthophosphates) reacting with the soil constituents at the upper horizons are greater than the lower horizons due to ponding. This accounted for the higher P sorption observed at the upper horizon than the lower horizon. This corroborates the findings of Tening et al. [30] who observed that the amount of P sorbed in the soil profile decreased significantly with soil depths.

With reference to P sorption according to the different land-use systems, more P was sorbed at soil depths of 0-5 and 5-10 cm in soils under the arable land than soils under the cocoa plantation. Conversely, more P was sorbed in soils under the cocoa plantation than the arable land at soil depth of 10-15 cm. As observed earlier in section 3.1, most of the measured chemical properties of soil under the cocoa plantation favoured more P sorption than soil under the arable land.

Thus, the differences recorded in P sorption capacities between the two land-use systems cannot be interpreted using the reaction of P with aluminium and iron oxides and, the exchangeable cations alone. The phenomenon which resulted in lower P sorption at soil depth of 0-5 and 5-10 cm in soils under the cocoa plantation than the arable land was attributed mainly to higher SOC, hydraulic conductivity and faster water flux density in soils under the cocoa plantation. Soil organic matter and clay content are known to be the major soil constituents to which most chemicals sorb [13].

But the organic molecules released upon the decomposition of organic matter reduce P fixation by either competing for sorption sites on Fe and Al oxides or forming complexes with Fe and Al in the soil thereby blocking the sites which are mainly responsible for fixation of phosphorus in the soil [31-33]. Consequently, higher SOC in soil under the cocoa plantation hindered their sorption capacity in comparison to the arable land. This also indicates that SOC could determine P availability in soils. The speed and ease with which the P solutions flowed through the soil matrix of soils under the cocoa plantation hindered their sorption capabilities in relation to the arable land.

The contact time of P reactions with the soil constitutes increased as a result of the prolong ponding in soils under the arable land and this increased their sorption capacity.

The differences observed in the sorption capacities of the two soils suggest that blanket application of P fertilizers to increase crop yield could cause the P to leach. The P content of the soil and the sorption capacity should be determined in order to know the right amount of P to apply. Differences in the sorption capacities also indicate that industrial wastewater (in the form of run-off) from off-sites could potentially cause the leaching of P into groundwater especially, where the groundwater table is shallow and, water flux and hydraulic conductivity are high.

The average concentration of total phosphorus (inorganic and organic forms) in wastewater has been reported to vary in the range of 10-20 ppm [34].

The higher P observed in the cocoa plantation than the arable land at soil depth of 10-15 cm suggested that different results could have been achieved if the batch equilibrium method was used to observe the P sorption phenomenon. This is due to the fact that most of the chemical properties favoured more sorption of P in soil under the cocoa plantation than soil under the arable land.

Batch equilibrium experiments involve adding known concentration of a chemical (e.g. P) to a known mass of soil and the mixture shaken at known revolution per minutes at specified time interval. The P sorbed by the soils in this experiment is determined by subtracting concentrations of P obtained from the mixture from the initial concentration of P solution applied. That is:

$$P \text{ sorbed (soil)} = \text{known P concentration} - P \text{ in the mixture} \quad (3)$$

The study thus indicated that using the typical sorption experiments (e.g. batch equilibrium) alone to investigate P sorption capabilities in accordance to soil depths poses serious concerns since the reaction of an infiltrating P solution with soil constituents in the upper soil profiles may not be the same as the lower horizon. Column experiments could give a better understanding of P leaching dynamics in soils.

Table 17 Sorption of phosphorus at different soil depths

Treatments	0-5 cm	5-10 cm	10-15 cm	^s Lsd (5 %)	CV (%)
Arable land	38.15	32.49	12.33	5.42	8.60
Cocoa	23.36	22.03	17.71	2.47	5.20
*p	0.001	0.021	0.016	-	-

^sLsd values were used to separate between means in terms of the P sorbed at varying soil depths within each land use type while *p (T test) values were used to compare P sorption between both land use systems at each soil depth.

4. CONCLUSION AND RECOMMENDATION

The vertical distribution of phosphorus through the soil column decreased significantly with soil depths in soils under both land-use systems. The soil under the arable land sorbed more P than the cocoa plantation soils at soil depths of 0-5 and 5-10 cm. The contrary occurred at a soil depth of 10-15 cm where more P was sorbed by soil under the cocoa plantation. The study showed that soil organic matter content, hydraulic conductivity and water flux density could hinder the sorption capacity of soils. Also, the impact of aluminium and iron to fix phosphorus is hindered by the above factors.

The differences observed in the P sorption capacities of the soils suggest that the use of blanket phosphate fertilizer recommendations may not be a good strategy as it may lead to under application or over application of P in some areas with the consequence of compromising crop yields or freshwater quality. Methods involved in the calculation of the amount of P to apply should take into account the sorption capacity of the soil.

The hypothesis that Fe, Al and Ca play the major role in influencing P sorption in accordance to soil depth was rejected based on the finding that, other soil properties such as soil organic carbon, hydraulic conductivity and water flux density could also play a greater role.

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