

Full Length Research Paper

Concentration, isomorphous substitution and phosphate sorption of extractable iron and aluminum oxides in Hadejia-Jama'are wetland soils, Nigeria

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Most iron nodules have micropores as a result of isomorphous substitution of aluminum (Al) for Iron (Fe). Hadejia-Jama'are wetlands is currently facing serious threat of rapid growing weeds associated with poor phosphate management. The objectives were to study the concentrations of dithionite and oxalate Fe and Al oxides, degree of aluminum substitution and phosphate sorption index of Hadejia-Jama'are wetlands. Three wetland locations and corresponding drylands (control) were selected. On each of the six research fields, soil samples were collected at 0 to 35, 35 to 70, 70 to 105 cm soil depth, replicated three times and composited. Oxides of Fe and Al were extracted. Phosphate sorption experiment was also conducted with 0, 100, 200, 400 and 800 mg P kg⁻¹. Phosphate ions sorbed were estimated as P applied minus P in the filtrate. Phosphate sorption index was established as $PSI = S/\log Ct$. From the results obtain, the iron fraction extracted with acid ammonium oxalate (Feo) was discovered to be an effective P sink. All the surface soils in the wetland areas revealed higher degree of Al substitution compared to the subsurface soils. About half of the added P in the wetland surface soils was released into the soil solution and more than half of the added P in the surface soil of the northern dryland was released into the soil solution and two-third of the added P in the surface soils of western and southern dryland locations were released into the soil solution. Hadejia-Jama'are soils sorb very little P when applied in small doses.

Key words: Phosphate, extractable-fe and Al oxides, isomorphism, sorption, wetlands.

INTRODUCTION

Wetlands are very productive areas that perform essential ecological functions such as; mitigation of climate change, aquatic habitation, stream flow maintenance, water purification, conservation and ground water recharge, sink of both inorganic and organic materials, and most importantly perform dual function for both dry and rainy season crop production. The nature and abundance of free Fe and Al oxides in soils can

complicate phosphate management practices especially to unprofessional farmers. The prevailing poor fertility management practices in Hadejia-jama'are wetlands include and not limited to rampant fertilizer application without checking the abundance of free Fe and Al oxides as well as the inherent fertility condition of the soils in the area. Most farmers around the area are completely ignorant of Fe an Al sesquioxides and their effect

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on phosphate ions. The nature, concentration and distribution of extractable Fe and Al oxides in soils can significantly affect the charge characteristics and intensity of anion adsorption especially phosphate ions (Agbenin, 2003). Existing information revealed that some of the central Fe^{3+} in an octahedral iron mineral can be replaced isomorphically by Al^{3+} co-existing in the same pedo-environment and this process can reach its maximum possible extent in Savanna Alfisols (Agbenin, 2003). The effect of this substitution usually give rise to structural distortion that create pore spaces in the iron mineral which consequently leads to an increase in the surface area and anion retention potential of the mineral through which anions such as phosphate ions may diffuse and become occluded (Agbenin, 2003). Tiessen et al. (1991) studied some Fe nodules using x-ray microprobe and discovered they contain high concentration of aluminum, further investigation using micro-morphological device revealed significant pores on them and he referred to those nodules as "ferruginous Fe nodules" or major sinks of P in Alfisols. Torrent (1987) opined that P seems to interact more with iron extracted with dithionite (Fe_d) than with iron extracted with acid ammonium oxalate (Fe_o) and Wang et al. (1991) added that P interact more with iron extracted with acid ammonium oxalate (Fe_o) than the crystalline iron fraction (Fe_{d-o}). So far, no systematic investigation was carried out in Hadejia-Jama'are wetlands to examine the effects of extractable Fe and Al oxides on P sorption capacity of the soils and such data will be very useful in designing P management methods in wetland soils. The phosphorus sorption index (PSI) is the ratio between the amounts of P contents adsorbed and the logarithm of the P concentration at equilibrium. It measures the ability of a given soil to remove P from soil solution and hold it on the soil surfaces or absorb it into the soil matrix, in other words it is the ability of soil to retain or release P into the soil solution. High PSI indicate high ability for soil to tie-up P, indicating high Fe and Al oxyhydroxides such as goethite, hematite, gibbsite and kaolinite in the clay fraction of the soil in question and vice-versa, also low PSI indicate that the soil in question will lech P easily and consequently pollute both the open water bodies via run-off and underground waters through leaching. Generally, the higher the PSI the greater the ability for P retention and the low the threat associated to water quality. The specific objectives of this study were to carry out a systematic investigation on the concentrations of dithionite and oxalate extractable Fe and Al oxides, the extent of aluminum substitution and the intensity of phosphate sorption in Hadejia-Jama'are wetland soils, Nigeria.

MATERIALS AND METHODS

Soil samples were collected from six different research locations (three wetland locations; northern wetlands, western wetlands, southern wetlands and their corresponding adjacent drylands as control). On each of the six research fields, disturbed soil samples

were collected at 0 to 35, 35 to 70, 70 to 105 cm soil depths, replicated three times and composited.

Samples were immediately transferred to air-sealed plastic bags, labeled appropriately and transported to the laboratory. Samples were air dried, further crushed using mortar and pestle, then sieved through 2 mm mesh to remove materials greater than 2 mm and then stored at 4°C in the refrigerator. Total free iron and aluminum oxides (Fe_d and Al_d) were extracted with sodium dithionite-citrate-bicarbonate representing the non-crystalline plus crystalline fraction while the amorphous iron and aluminum oxides (Fe_o and Al_o) were extracted with acid ammonium oxalate in the dark (Jackson et al., 1986) representing the non-crystalline iron and aluminum oxides fraction and then the crystalline fraction was estimated by difference as follows Fe_{d-o} and Al_{d-o} (Agbenin, 2003) where Fe_d and Al_d are iron and aluminum extracted with sodium dithionite-citrate-bicarbonate and Fe_o and Al_o are iron and aluminum extracted with acid ammonium oxalate.

Oxides of Fe and Al in the filtrate were determined using Microwave Plasma Atomic Emission Spectrophotometer (MP-AES) at multi-user laboratory, Department of chemistry, Ahmadu Bello University Zaria. Degree of isomorphous substitution of Al for central metal Fe in octahedral Fe oxide mineral was also determine as mol%Al using the dithionite-citrate-bicarbonate and acid ammonium oxalate fractions extracted are as follows molar concentration of Fe_{d-o} / molar concentration of $\text{Fe}_d + \text{Fe}_{d-o}$. Phosphate sorption experiment was conducted using varied concentrations of P sources at 0, 100, 200, 400, 800 mg P kg^{-1} and added it to 5g of each of the soil samples, using KCl and two drops of 0.5 mL chloroform, shake for 30 minutes daily, equilibrated for 7 days. Sorbed P was estimated as P applied minus P in the filtrate. Phosphorus sorption index was established as $\text{PSI} = S \text{ (mgkg}^{-1}) / \log \text{Ct (mg L}^{-1})$, where S is the P sorbed (native P + added P – P in the filtrate) while Ct is the concentration of P in the filtrate or (P at equilibrium).

RESULTS AND DISCUSSION

The concentration of total free iron oxides

The concentration of total free iron oxides iron fraction extracted with Sodium dithionite-citrate-bicarbonate (Fe_d) is shown in Table 1. The range of values obtained in the dryland soils were high 9.42 to 23.79 gkg^{-1} compared to 3.08 to 13.07 gkg^{-1} obtained in the wetland soils, probably due to the anaerobic condition of the wetland soils which makes ferric iron more soluble and prone to leaching or co-migrate with clays; or due to high organic matter content in the wetland soils that may have promoted metal-fulvate-interaction, making the ferric ions more soluble and more reactive to organic chelates, there by forming complexes or due to high isomorphous substitution by Al for Fe, or may be due to high plant uptake both during rainy season and irrigation season and by aquatic plants in the wetland soils. It may also be due to combine effect of all the factors stated above. On the other hand, improved aeration and low rainfall in the dryland areas may have resulted to a year-round accumulation of iron oxides, unlike in the wetland soils where there is tendency of continuous push of soluble products by rainfall, flood water, irrigation water and/or co-migration with clays beyond the soil depths selected for this research work.

Table 1. Extractable Fe and Al oxides, isomorphous substitution and p sorption index of Hadejia-Jama'are River Basin.

Treatment	Depth (cm)	Fe _d	Fe _o	Fe _{d-o} (gkg ⁻¹)	Al _d	Al _o	Al _{d-o}	DIS (mol % AL)	P sorbed (mgkg ⁻¹)	P sorbed % of applied	PSI
NwHJRB	0-35	9.31	6.89	2.42	3.56	2.15	1.41	26	797	53	242
	35-70	11.66	4.08	7.58	2.83	1.03	1.80	20	566	38	169
	70-105	13.07	0.34	12.23	3.72	2.63	1.09	12	545	36	156
WwHJRB	0-35	8.18	7.84	4.51	5.51	2.00	3.51	20	642	43	198
	35-70	12.72	3.67	4.88	3.13	2.15	1.98	20	588	29	169
	70-10	3.08	0.59	2.49	1.53	1.42	0.12	4	312	21	103
SwHJRB	0-35	9.18	8.56	1.25	6.50	1.37	5.13	22	875	58	252
	35-70	11.65	4.22	7.43	2.98	1.49	1.49	17	613	41	190
	70-10	5.25	2.90	2.35	4.98	2.78	2.04	15	503	34	144
Drylands											
NdHJRB	0-35	10.98	7.93	2.02	5.84	2.51	3.33	18	602	40	181
	35-70	12.06	4.81	7.25	3.36	1.00	2.36	21	678	45	202
	70-105	22.77	9.73	13.04	4.17	2.12	2.05	17	419	28	149
WdHJRB	0-35	11.58	9.32	2.26	4.34	1.19	3.15	16	451	30	128
	35-70	14.52	7.92	6.6	3.12	1.10	2.02	20	484	29	120
	70-105	23.79	3.20	20.59	3.11	1.92	1.92	14	337	22	109
SdHJRB	0-35	9.42	8.08	1.34	2.26	1.13	1.13	17	473	32	143
	35-70	22.37	4.78	17.59	2.88	1.65	1.65	18	587	39	169
	70-105	20.98	3.21	17.77	2.93	1.16	1.16	13	321	21	107

Fe_d = iron extracted with dithionite-citrate-bicarbonate, Fe_o = iron extracted with ammonium oxalate, Al_d = aluminum with dithionite-citrate-bicarbonate, Al_o = aluminum extracted with ammonium oxalate, DIS = degree of isomorphous substitution (of Al³⁺ for Fe³⁺), PSI = Phosphate sorption index, N = northern, W = western, S = southern, w = wetlands d = drylands, HJRB = Hadejia-Jama'are River Basin, Trt = treatments.

Source: Author.

The concentration of amorphous iron oxides

The concentration of iron oxides extracted with acid ammonium oxalate (Fe_o) is shown in Table 1, the range of values obtained was 3.20 to 9.73 gkg⁻¹ in the dryland soils and it was higher compared to 0.34 to 8.56 gkg⁻¹ in the wetland soils. Values reported here are higher than the values 0.08 to 0.18 gkg⁻¹ observed by Agbenin (2003) in savanna Alfisols and 0.25 to 1.12 gkg⁻¹ observed by Abdu (2006) but are close to the range of values 1.43 to 6.43 gkg⁻¹ observed by Maniyunda et al. (2015) in soils developed on basement complex of northern Guinea savanna of Nigeria and in consonance with the range of values 2.7 to 10.9 gkg⁻¹ reported by Olatunji et al. (2015) but significantly lower than the range of values 1.03 to 33.87 gkg⁻¹ reported by Aliyu (2018). Variations above may be attributed to difference in parent material especially the underlain rock, vegetation, climatic conditions, internal drainage and landscape of the various locations where the various researches above were carried out. The values of the Fe_o decrease drastically down the soil profile across all the wetland

soils and decrease gradually in western and southern drylands except in western wetlands where there is inconsistency in the distribution down the soil profile. High amorphous iron (Fe_o) in the wetland surface soil may fix large amount of P, supporting the general thought that, wetland soils are source and sink of P.

The concentration of crystalline iron oxides

The concentrations of the crystalline iron oxide (Fe_{d-o}) (Table 1) were estimated by the difference between Fe_d and Fe_o (Agbenin, 2003). The values recorded in Hadejia-Jama'are wetlands 1.25 to 12.25 gkg⁻¹ were low compared to the values 1.34 to 20.59 gkg⁻¹ recorded in the adjacent dryland soils. The value of this fraction is often neglected in most researches. Most pedologists reports the ratio of Fe_o to Fe_d (Fe_o/Fe_d) in order to measure the degree of crystallinity of soils, and use it to distinguish hardness or difference in plinthization (pedogenic development, or degree of soil aging) and also measures extent of weathering (Samdi, 2012;

Maniyunda et al. 2015). Although, they have clearly explained that, low ratio is an indication of high degree of crystallinity. Values obtained in the drylands show drastic increase down the soil profile and highly concentrated at subsurface depth of 70 to 105 cm but values show irregular pattern in the wetlands. Fe_d seems to be misquoted by some researchers like Wang et al. (2013), who reported it as crystalline iron fraction instead of total free iron oxides consisting of both crystalline and amorphous iron oxides (Mehra and Jackson, 1960; Samdi, 2012, Maniyunda et al., 2015) otherwise considered to be the poorly crystalline Fe oxides while Fe_o is the amorphous so that the difference between the two is the crystalline fraction (Agbenin, 2003). However, Olatunji et al. (2015) opined that either of the two can be considered crystalline. Significant interaction observed between the land forms and the soil depths may be attributed to high amount of crystalline Fe oxides due to improved aeration in the dryland soils and may also be the same reason behind the significant variations observed down the soil sampling depths, showing deposition and crystallization of Fe oxides in the sub-surface soils.

The concentration of total free aluminum oxides

The concentration of total free aluminum oxides (Table 1) the aluminum fraction extracted with sodium dithionite-citrate-bicarbonate (Al_d) ranged from 1.53 to 6.5 gkg^{-1} in the wetlands and from 2.26 to 5.84 gkg^{-1} in the dryland soils. Values shows a consistent decrease down the soil profile in the wetlands except in northern wetland where an irregular distribution pattern was observed. A gradual decrease was observed in the drylands except in southern wetland where the concentration slightly increased down the soil profile. Values obtained here were high compared to values 0.57 gkg^{-1} to 2.45 gkg^{-1} observed by Agbenin (2003) and 0.10 gkg^{-1} to 2.13 gkg^{-1} observed by Maniyunda et al. (2015) and are generally low compared to the values 2.9 to 43.3 gkg^{-1} reported by Olatunji et al. (2015) and Aliyu (2018) reported 1.37 to 43.79 gkg^{-1} .

The concentrations of amorphous aluminum oxides

The concentration of amorphous aluminum oxides (Table 1), the aluminum fraction extracted with acid ammonium oxalate (Al_o) ranged from 1.03 to 2.70 gkg^{-1} in the wetland soils and 1.00 to 2.51 gkg^{-1} in the dryland soils. Most occurring higher values were recorded in the wetlands but the highest value was recorded in the drylands, this is because values recorded in the wetland soils are dominantly above 2 gkg^{-1} unlike the dryland soils with predominant values slightly above 1 gkg^{-1} . This shows high concentration of soluble aluminum in wetland soils compared to the dryland soils, attributed to intense

weathering, mobilization, transport and deposition of soluble aluminum downslope, since aluminum is not affected by redox reaction and probably substituted into iron oxides isomorphically, especially in the dryland soils. Values reported here are higher compared to the range of values (0.15 to 0.70 gkg^{-1}) obtained by Agbenin (2003) and (0.15 to 0.40 gkg^{-1}) reported by Abdu (2006) but very low compared to (1.3 to 87 gkg^{-1}) reported by Olatunji et al. (2015) and (0.31 to 27.26 gkg^{-1}) reported by Aliyu, (2018).

The concentrations of crystalline aluminum oxides

The concentrations of the crystalline aluminum oxides (Al_{d-o}) (Table 1) were estimated by difference between Al_d and Al_o (Agbenin, 2003). Values recorded in Hadejia-Jama're wetlands ranged from 0.12 to 5.13 gkg^{-1} while values obtained in the drylands ranged from 1.13 to 3.33 gkg^{-1} . The highest value was recorded in the surface soil surface soil of southern wetland; however, predominant higher values were recorded in the dryland soils which may be due to low aluminum substitution in the drylands and also due to improved aeration in the drylands.

The degree of isomorphous substitution of Al for Fe in octahedral iron mineral structure

The degree of Isomorphous substitution (Table 1) of Al^{3+} for Fe^{3+} in octahedral iron oxide mineral structure (DIS) in Hadejia-Jama'are soils was estimated as mol%Al. Values obtained ranged from 4 to 26 mol%Al in the wetland soils and 13 to 21 mol%Al in the dryland soils and values were in harmony with the range of values 11 to 29 mol%Al reported by Agbenin (2003) in savanna Alfisols. Interestingly the lowest value 4 mol%Al and the highest value 26 mol%Al were recorded in the wetland soils, probably associated to lithologic discontinuity due to deposition by flooding in the wetland soils that may have cause high deposition of clay at some point and little deposition at other points which gave rise to a lopsided association of Al and Fe in fine clay fractions. However, most of the frequently occurring higher values were generally recorded in the wetland soils compared to the values obtained in the dryland soils, indicating high aluminum substitution in the wetland soils which will consequently promote high P sorption in the wetlands due to increase in surface area of the clay minerals resulted from structural distortion in Fe oxide minerals. The DIS in the wetlands show consistent decrease from surface to sub-surface in all the wetland soils, indicating higher degree of Al substitution in the wetland surface soils which consequently leads to high P sorption in the surface soils compared to sub-surface soils as revealed by the P sorption values across the wetlands indicating that the higher the DIS the higher the P sorption, suggesting high unit surface area which indicate the presence of a substituted goethite than pure goethite

Table 2. Phosphate sorption of Hadejia-jama'are soils.

Depth (cm)	NHJRB (ppm)					WHJRB (ppm)					SHJRB (ppm)				
	0	100	200	400	800	0	100	200	400	800	0	100	200	400	800
Wetlands															
0-35	-	10	19	216	553	-	04	30	137	432	-	04	87	231	484
35-70	-	04	21	131	410	-	02	90	130	345	-	02	86	106	406
70-105	-	03	11	130	402	-	08	08	181	115	-	08	77	140	280
Uplands															
0-35	-	08	70	164	360	-	08	08	114	321	-	07	14	133	320
35-70	-	12	16	125	526	-	08	14	134	329	-	04	35	170	378
70-105	-	02	83	83	224	-	03	12	111	212	-	04	05	011	301

HJRB = Hadejia-Jama'are River Basin, N = northern, W = western, S = southern.

Source: Author

than pure goethite (Agbenin, 2003). The trend in the drylands show slight increase from 35 to 70 cm and decrease down the soil profile from 70 to 105cm soil depth, indicating highest degree of Al substitution within 35 to 70 cm probably due to significant clay deposition in the lower B-Horizon. This may imply that should the surface soil be eroded from 0 to 35cm, P sorption will manifest dramatic increase.

Phosphate sorption of P in Hadejia-Jama'are Soils

The phosphate sorption (Table 2) in Hadejia-Jama'are river basin increased consistently with increase in P loading. The P sorption pattern down the soil profile revealed a sharp decrease between the surface and the sub-surface soils, across all the wetland soils and this may be due to high organic material and suspended clay particles deposited by run-off and overlaying flood water. The sub-surface soil 35 to 70 cm in the drylands showed high P sorption, followed by the

surface soil 0 to 35 cm probably due to argiluviation of clay particles that might have co-migrated with Ca and Mg ions in the lower B-horizon, due to short periods of rainfall that might have hindered continuous vertical movement of soluble products down the soil profile through tubular pores. This may also suggest that the surface soil should be eroded up to 35 cm P sorption will manifest a dramatic increase. The wetland soils showed high P sorption especially at the surface compared to the dryland soils, which could be due to clay deposition from up-slope into the wetland's surface soil or probably due to leaching and co-migration of clay particles associated with soluble Fe and Al ions beyond the depths selected for this research work, creating a bleached zone within 35 to 105 cm soil depth. May likely also be associated to vertical capillary up-thrust of clay particles by the water table and became deposited within 0 to 35 cm soil depth. May probably be due to combine effects of diffusion and fixation of P by Fe and Al due to high isomorphous substitution of Al in the surface soil than the sub-surface.

The phosphate sorption index of Hadejia-Jama'are wetland soils

Phosphate sorption index (PSI) is a biogeochemical index, which estimates the potential for a soil to retain additional amount of P without causing environmental threat (it's a specific and realistic estimate of P buffering capacity of soils).

The PSI values observed (Table 1) in Hadejia-Jama'are ranged from 103 to 252 in the wetland areas and 107 to 202 in the dryland areas. The PSI values are within the range of values (63 to 224) reported by Agbenin (2003) in Nigeria Savanna Alfisols and values (32 to 330) reported by Dunne et al. (2006) in lake Okeechobi Basin, Florida. There is sharp decrease in PSI down the soil profile across all the wetlands. PSI is almost twice in surface soils of northern and southern wetlands than there is in the sub-soils except in western wetlands. However, it is still much higher in the surface soil of western wetlands, than in the sub-soils, indicating high sorption capacity in the surface compared to the sub-surface. This can be

associated to high silicate clays in the surface than the sub-surface. The PSI is also higher in sub-surface 35 to 70 cm of all the wetlands compared to the sub-surface 70 to 105 cm. There is an alternating increase-decrease pattern in PSI down the soil profile across all the dryland soils except in western dryland which show consistent decrease from the surface to the sub-soils, similar to the trend observed in the wetland soils. PSI is much higher in the surface 0 to 35 cm and sub-surface 35 to 70 cm compared to the sub-surface 70 to 105 cm across the entire drylands. However, higher values (202, 169) were observed in the sub-surface 35 to 70 cm of all the drylands except in western dryland were almost the same values were obtained in both surface 0 -35 cm and sub-surface 35 to 70 cm but the values are still higher (128, 120) compared to the value (109) obtained in the sub-surface 70 to 105 cm, indicating that, these soils will be more vulnerable to leaching, compared to run-off of P ions. The difference in PSI observed among the surface and sub-surface soils may be attributed to variation in clay content and variation in the mol%Al that is isomorphically substituted for Fe. Hadejia-Jama'are wetlands generally show higher PSI compared to their corresponding drylands, providing more proof that PSI is in most cases a function of landscape position. The surface soils across all the wetlands sorb more P than sub-surface, associated to variation in clay content. This is in harmony with the findings of (Dunne et al., 2006) who observe much higher PSI in surface sediments compared to sub-surface sediments. Nguyen and Sikias (2002) also observe higher PSI values in surface drainage receiving run off from agricultural fields in New Zealand compared to sub-surface drainage soils. The higher the PSI the greater the ability for P retention and the low the threat associated to water quality, because amount of P sorbed by a given soil, is a function of sorption and in most cases a function of landscape position (Dunne et al., 2006).

Conclusion

Based on the findings from this work, Fe extracted with acid ammonium oxalate (Fe_o) was discovered to be an effective P sink. The DIS shows consistent decrease from surface to sub-surface in all the wetland soils, indicating higher degree of Al substitution in the wetland surface soils which consequently leads to high P sorption in the surface soils compared to sub-surface soils as revealed by the P sorption values across the wetlands indicating that the higher the DIS the higher the P sorption, suggesting high unit surface area which indicate the presence of a substituted goethite than pure goethite. Slight increase in P sorption from soil depth 35 to 70 cm indicate high degree of Al substitution within that soil depth, probably due to significant clay deposition in the lower B-Horizon, the implication is that should the surface soil be eroded from 0 to 35 cm, P sorption will manifest

dramatic increase. A critical observation on the sorption experiment revealed that, almost half of the added P in the wetland surface soils was released into the soil solution and more than half of the added P in the surface soil of the northern dryland was released into the soil solution and two-third of the added P in the surface soils of western and southern dryland locations were released into the soil solution indicating that these soils are prone to leaching and underground and open water eutrophication, even though part of the phosphate ions in the soil solution will be absorbed by plants. Hadejia-Jama'are soils sorb very little P when applied in small doses such as 100 to 200 mg P kg⁻¹ compared to when larger doses such as 400 to 800 mg P kg⁻¹ are added, this is because when 100 mg P kg⁻¹ was added, only about 2 to 12% was retained and the remaining were released in to the soil solution which could be quickly mobilized and swept away by run-off or leached down into the underground waters.

However, when moderate quantity of about 400 to 800 mg P kg⁻¹ was added, up to about 20 to 50% was retained, the implication is that, application of P fertilizer in very little doses will have very little impact on long-term nutrient supply to crops, even though application of a very large quantity may lead to eutrophication of both open and underground water bodies, therefore moderate quantity of about 300 to 600 mg P kg⁻¹ will be the most suitable dose for P fertilizer application in Hadejia-Jama'are soils and deep placement application method will be the most profitable method of P fertilizer application in these soils, as other application methods such as broadcasting, top or band placement methods may lead to great P loss in Hadejia-Jama'are soils capable of causing eutrophication of open and underground water bodies.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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