

AVAILABLE PHOSPHORUS FRACTIONS IN SOILS FROM DORO, KATSINA STATE, NIGERIA

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Abstract

Sustainable crop production in the Nigerian Sudan Savanna biome requires a good understanding of the fertility status of the soil for appropriate nutrient management strategies, yet phosphorus (P) reserves are rapidly being depleted. Agricultural soils, especially in the region are inherently poor in basic nutrients, including P. Field sampling was conducted to assess the phosphorus status of soils from Doro, Katsina State in the Northern Nigerian Sudan Savanna area. The sampled field was dominated by sand with a mean value of 62.66 % followed by clay (17.34 %) and silt (20.00 %). The soil was classified as sandy loam, with basic soil nutrients (organic C, total N, exchangeable cations and ECEC) within low to very low fertility classes. The soil was slightly acidic (pH 6.8) in reaction with total P (TP) of 97.89 mg kg⁻¹. Available (Bray's) P of 4.82 mg kg⁻¹ and the Olsen extracted P (1.27 mg kg⁻¹) were far too low compared with TP. These low available P values are indicative of soil nutrient depletion and degradation. Therefore, maintenance of soil P at a target value through application of P fertilizers, periodic incorporation of crop residue and organic manures would be very essential for soil P restoration and fertility management.

Keywords: Phosphorus; soil nutrient management; dryland; soil physico-chemical properties; Sudan savanna

Introduction

Phosphorus (P) is an essential nutrient for plant growth, and its availability in soils can significantly influence agricultural productivity, especially in the Sudan savannah. The Sudan savannah in sub-Saharan Africa is characterized by a semi-arid climate, typified by distinctive vegetation and soil types (Ariko *et al.*, 2019). Studies on soil P fractions in the area have focused on understanding the distribution, availability and dynamics of different forms of P in the soil (Murphy and Riley, 1962; Olsen and Sommers, 1982). Phosphorus is a key component of nucleic acid and stimulates root growth by enabling plants to explore a larger soil volume for water and nutrients (Guera *et al.*, 2020). It also enhances the development of fine root hairs, which increases the surface area of roots for improved nutrient absorption. Soil pH affects availability of P as acidic soils can bind P, making it less accessible to plants, while alkaline soils can precipitate P compounds that are less soluble (Teng *et al.*, 2020). The movement of P through various biological, chemical and physical processes in the soil and ecosystem is essential for maintaining soil fertility and the availability of P for plant uptake.

In Sudano-Sahelian soils, the availability of P is low due to reduced capacity to hold onto positively charged nutrient ions, which results in their loss through leaching or excessive irrigation. In such soil, it may be necessary to supplement P through fertilization to meet plant's needs. The soil Olsen P method has been found to be a reliable and accurate way to predict phosphorus availability, especially in areas with high pH (>7.0) soils. It provides valuable information to farmers on decisions about fertilizer applications for optimum yield

and improved soil health. It involves extracting a soil sample with an Olsen solution, which is a mixture of water, calcium chloride, and ammonium nitrate. It has been widely used to assess phosphorus availability for crops. A recent study by Ibrahim *et al.* (2021) found that the Olsen P method accurately predicted phosphorus availability in soils, making it a useful tool for fertilizer recommendations.

The Sudan savanna belt is in northern Nigeria and extends from the Chad Basin to northern portion of the Nigerian High Plains. It encompasses more than 25 % of Nigeria, including the regions surrounding Sokoto, Katsina, Kaduna, Kano, and the Borno States. The zone has the largest population density in Northern Nigeria and experiences a dry season of about 6-7 months apart from a few rainy months when it can increase to 60 % or more, the relative humidity typically hovers around 40 % and the rainfall ranges between 600 and 1000 mm (Sawa *et al.*, 2015; Ariko *et al.*, 2019). Daytime temperatures can fluctuate greatly, from 15 °C at night to over 40 °C during the day (Sandwidi, 2007). The sub-soils have a clayey texture with sandy to loamy topsoil, coupled with high rainfall intensities. The region is very susceptible to erosion (Callo-Concha *et al.*, 2019). Frequent droughts and a significant rainfall fluctuation are key characteristics of the Sudan savanna. As a result, soil fertility is poor and a major constraint to agriculture in the region. Compared to the Guinea savanna, there is less vegetation in this area that could facilitate soil nutrient cycling.

Sustainable crop production aims at maintaining high crop yield without adversely affecting ecosystems to meet the need of current as well as future generations (Tilman *et al.*, 2002). Since phosphorus is the second most growth limiting macronutrient after nitrogen, its proper management in soil contributes significantly to sustainable crop production. Maintaining an optimum soil pH is not only of agronomic interest but also an economic one. Phosphate fertilizer and soil phosphate therefore should be used efficiently. Despite the relatively small amount of phosphate in the soil solution at any given time, plants can take up substantial amounts due to replenishment of the solution phosphorus pool through desorption from soil particles and dissolution from soil minerals. Uptake of phosphate by plants creates a strong diffusion gradient that moves phosphate toward plant roots at a higher rate relative to water uptake driven by transpiration (Eckardt, 2005). The P fractions in manures, including composts, are dependent on various factors, like the type, solid-liquid separation status, decomposition rate, and handling processes and storage (Eneji *et al.*, 2003; Pagliari and Laboski, 2013). Understanding the distribution and proportions of different P fractions in Sudan savannah soils is crucial for effective soil fertility management. Soil testing and analysis techniques, including fractionation methods can provide valuable information on the relative abundance of each P fraction. Based on the results, appropriate soil management strategies, such as P fertilizer application, organic matter additions, pH adjustments, and erosion control, can be implemented to optimize P availability and enhance soil fertility.

This study was conducted to develop a robust database of the current conditions of soil to predict the behavior and fate of P during fertilizer recommendations, and to identify sustainable field management practices to reduce possible P losses.

Materials and Methods

The study location was Doro (12° 47.357' N; 7° 54.814' E) in Katsina State, Nigeria (Figure 1). Katsina state transverse the Sudan Savannah zone of Nigeria, and it is among the frontline states under threat of desert encroachment from the Sahara. The area is dominated by grass species and few shrubs and trees, with a mean rainfall of about 700 mm per annum and a dry season lasting 6-7 months. The altitude varies between 326 and 1231 m asl but the average altitude of the pilot site was ≤ 540 m above sea level.

Soil sample collection and preparation

A one-hectare plot was established for grid sampling of 25 m apart with 25 composite core soil samples (Figure 2) from 0-30 cm depth. The composite samples were air-dried, ground, and screened via a 2 mm sieve for the determination of total P and extraction of inorganic P fractions.

Total phosphorus (TP)

The TP was determined by placing 2.0 g soil sample in a 300 mL conical flask and adding 30 mL perchloric acid (HClO_4) and digesting at 130°C . The resulting colorless solution was cooled, and 50 mL distilled water was added and filtered. The color was determined using ascorbic acid to form highly colored molybdenum blue and weighed in a spectrophotometer at 882 nm.

Acid-extractable available phosphorus (AP)

This was extracted with acidic fluoride using the Bray P1 method (Bray and Kurtz, 1945); phosphorus in the extract was then determined by the molybdenum blue method of Murphy and Riley (1962).

Bicarbonate-extractable (Olsen) available phosphorus (OP)

This was determined according to Kuo (1996); sieved soil (5 g) was treated with 100 mL of NaHCO_3 (pH 8.5) in a 250 mL Erlenmeyer flask and shaken for 30 min. The mixture was filtered, and the extract was used to determine the P concentration.

Statistical analysis

Data collected were subjected to descriptive analysis of mean, standard deviation and coefficient of variation.

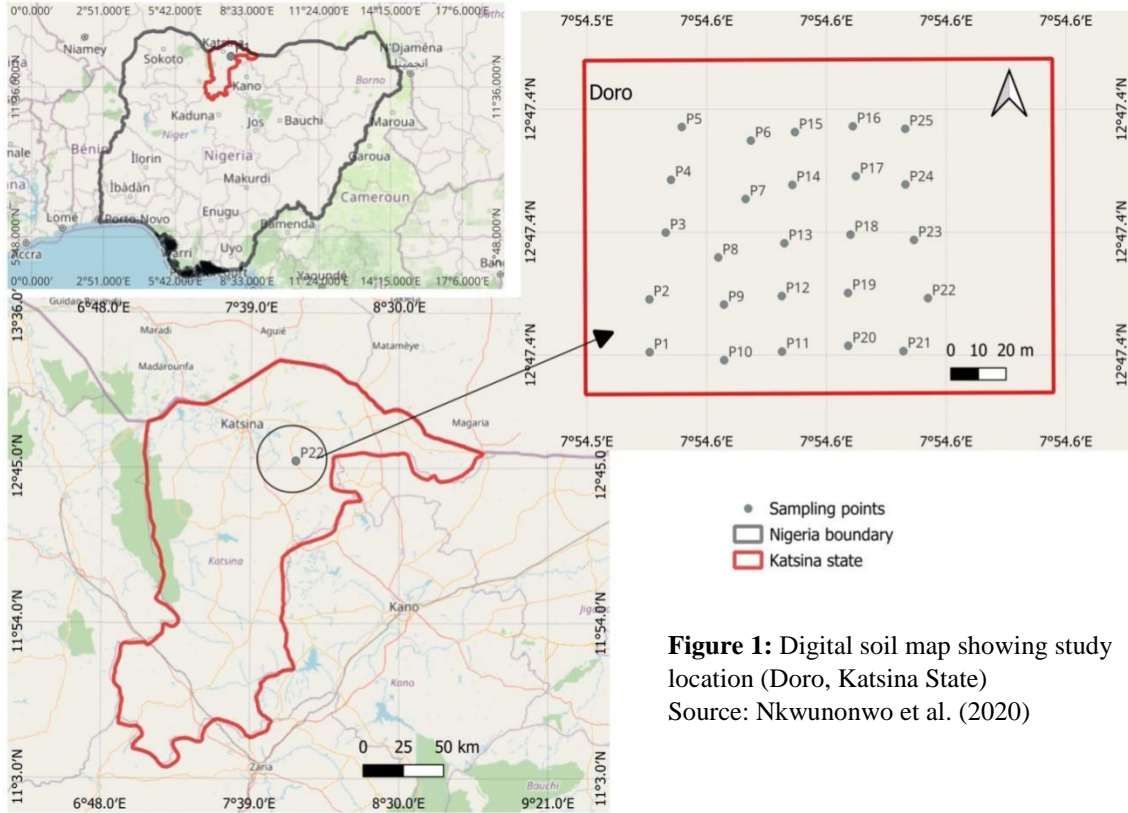


Figure 1: Digital soil map showing study location (Doro, Katsina State)
Source: Nkwunonwo et al. (2020)

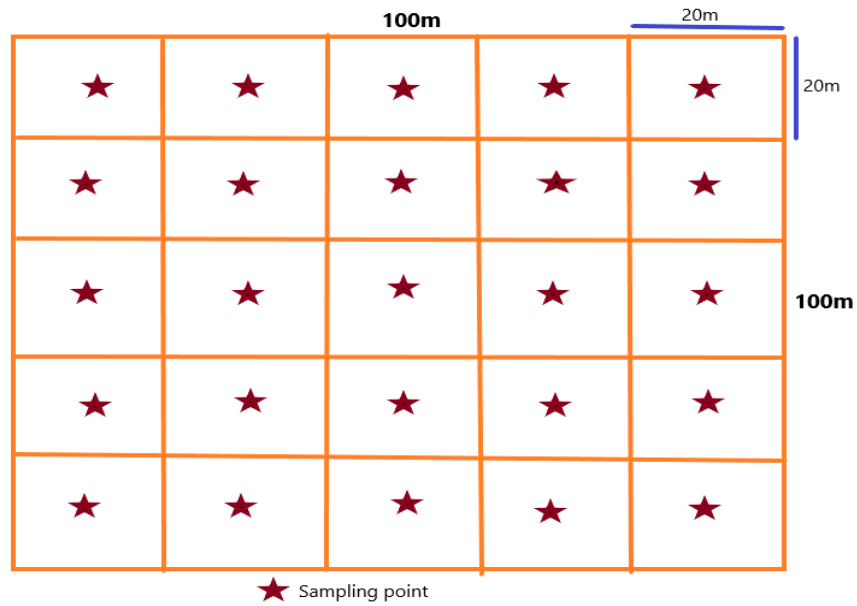


Figure 2: Grid sampling scheme

Results and Discussion

The physicochemical transformations of P (dissolution, precipitation, adsorption and desorption) are regulated by soil pH, organic matter content and soil biological properties (Yu et al., 2021). The physicochemical properties of the soil in the study area (Table 1) showed that the soil was dominated by sand with mean value of 62.66 % followed by clay (17.34 %) and silt (20.00 %). The soil was classified as sandy loam with a mix of both fine and coarse particles which are well-suited for growing a variety of crops due to their ability to retain moisture while still allowing for good drainage. The soil reaction was rated to be slightly acidic with a mean pH value of 6.8 and a range of 6.2-8.0 which is optimal for overall satisfactory availability of plant nutrients (Brady and Weil, 2002). The soil organic carbon (%) was very low (0.50) as was the total nitrogen (0.03 %). The low organic carbon is typical of Sudano-Sahelian soil. In Sudan-Sahelian soils, the levels of OC and TN vary widely depending on factors such as climate, vegetation, and land management practices. It has been found that OC levels in Sudan-Sahelian soils were generally low (averaging around 1.5 % in the topsoil layer) because of the region's hot and dry climate, which hastens organic matter decomposition and limits its accumulation (Bationo *et al.*, 2017; Bienvenu *et al.*, 2023). Improving soil health through the application of organic amendments and the adoption of sustainable land management practices are essential for maintaining OC and TN levels for optimal crop production. The exchangeable cations and ECEC were also generally well below the recommended values for agricultural soils and so would need improvements through appropriate management.

Changes in Soil Phosphorus (P) Fractions

The data for total and available P fractions are shown in Table 2. The total phosphorous concentrations ranged from 53.75 to 258.75 mg kg⁻¹ soil, with a mean value of 97.89 mg kg⁻¹. These values are low compared with the sufficiency limit of 500 to 800 mg kg⁻¹ dry soil (Porder and Hilley, 2011). Soil-available phosphorous extracted with acidic fluoride ranged from 1.12 to 15.50 mg kg⁻¹ with a mean value of 4.82 mg kg⁻¹ soil (Table 2). These values are considered low, based on the critical limit of >20.0 mg kg⁻¹ for Sudano-Sahelian soils (Shehu *et al.*, 2015). This might be partly related to their inherent low status, such as the parent materials which are mainly of Aeolian origin, with low weatherable mineral reserve necessary for nutrient recharge (Manu *et al.*, 1991) and partly to the complete crop residue removal by the farmers or annual bush burning in the study area. Phosphorus is a key nutrient in intensive agricultural production as it is essential for crop growth and yield (Haslam *et al.*, 2019). However, resource limitation and chemical P-induced environmental pollution are the global challenges. Understanding the distribution of different inorganic and organic P fractions is a prerequisite for the monitoring and estimating phosphate transformation in soils.

Most Nigerian Savanna soils are highly weathered and fragile with low activity clays, and of low fertility due mainly to continuous arable cropping (FFD, 2012). Generally, soil productivity declines rapidly when vegetation cover is lost and under inappropriate management practices resulting in soil organic matter depletion. The use of mineral fertilizer in Nigeria has been often low with an average application of nutrient per hectare of arable land estimated at 5.7 kg, compared to the world average of 133.5 kg (World Bank, 2010). Among the problems associated with poor mineral P fertilizer use in Nigeria, is that of recommendations which are semi-site specific since they are based on soil characteristics.

The soil Olsen-P ranged between 0.72 and 2.92 mg kg⁻¹, with a low mean value of 1.27 mg kg⁻¹ (Table 2). For the Sudano-Sahelian soils of West Africa, the critical limit is generally set at around 15-20 mg kg⁻¹ (Ibrahim *et al.*, 2021). This means if the Olsen-P level in soil sample



falls below this range, it suggests that there may be a deficiency of available phosphorus in the soil. This can negatively impact plant growth and productivity, as phosphorus is an essential nutrient for plants. A recent study found that Olsen-P levels below 15 mg kg^{-1} were associated with reduced plant growth and productivity in Sudano-Sahelian soils (Ibrahim *et al.*, 2021). Mancini *et al.* (2024) reported that Olsen-P levels below 20 mg kg^{-1} were indicative of P deficiency. These reports suggest that the soil under study is highly deficient in P. Phosphorus plays a crucial role in processes such as photosynthesis, root development, and flower and fruit production. Without sufficient phosphorus, plants may experience reduced growth, stunted development, and decreased yields (Haslam *et al.*, 2019). By maintaining the available P level within or more than the critical range, farmers can ensure that their crops receive adequate supply of P, which can lead to improved plant health, increased resistance to disease and pests, and higher crop yields. Maintaining optimal P levels can reduce the need for frequent fertilization (FDAR, 2004), which can help reduce environmental impacts and save costs for farmers.

Table 1
Statistical summaries of soil properties of Doro (Katsina State), Nigeria

Sample No.	Sand %	Clay %	Silt %	pH	Org. C %	TN %	Ex. Ca (cmol/kg)	Ex. Mg (cmol)	Ex. K (cmol/kg)	Ex. Na (cmol/kg)	Ex. H (cmol/kg)	ECEC (cmol/kg)	BS %
P1	64.3	22.7	13.0	7.2	0.84	0.07	7.8	2.2	0.25	0.20	0.0	10.45	100.00
P2	55.3	34.7	10.0	8.0	0.20	0.01	18.0	2.4	0.27	0.25	0.0	20.92	100.00
P3	68.3	11.7	20.0	7.6	0.40	0.03	3.2	1.4	0.20	0.18	0.0	4.98	100.00
P4	66.3	14.7	19.0	6.9	0.20	0.01	3.6	0.4	0.20	0.17	0.10	4.47	98.00
P5	64.3	15.7	20.0	6.4	0.20	0.01	2.4	0.8	0.22	0.19	0.30	3.91	92.00
P6	60.3	15.7	24.0	6.5	0.32	0.02	3.8	1.0	0.18	0.16	0.25	5.39	95.00
P7	63.3	18.7	18.0	7.3	0.38	0.02	6.0	0.4	0.24	0.20	0.0	6.84	100.00
P8	62.3	14.7	23.0	6.9	0.40	0.03	4.0	1.0	0.22	0.19	0.10	5.41	98.00
P9	59.3	21.7	19.0	6.9	0.60	0.05	4.8	1.4	0.21	0.18	0.14	8.51	98.00
P10	59.3	21.7	19.0	6.8	0.40	0.03	6.2	1.8	0.20	0.17	0.14	8.51	98.00
P11	60.3	20.7	19.0	7.4	0.30	0.02	6.0	2.0	0.23	0.20	0.0	8.43	100.00
P12	62.3	11.7	26.0	7.3	1.06	0.09	6.4	1.6	0.22	0.19	0.0	8.41	100.00
P13	59.3	19.7	21.0	6.4	0.50	0.04	4.0	1.6	0.18	0.15	0.28	6.21	95.00
P14	60.3	23.7	16.0	6.5	0.66	0.05	6.6	1.8	0.17	0.14	0.25	8.96	97.00
P15	61.3	15.7	23.0	6.3	0.48	0.03	2.8	1.2	0.20	0.18	0.30	4.08	93.00
P16	66.3	13.7	20.0	6.4	0.38	0.02	2.6	0.8	0.19	0.14	0.28	4.01	93.00
P17	69.3	9.7	21.0	6.6	0.74	0.06	4.0	0.8	0.25	0.22	0.24	5.51	96.00
P18	61.3	15.7	23.0	6.3	0.60	0.05	4.0	1.8	0.23	0.19	0.30	6.52	95.00
P19	65.3	14.7	20.0	6.2	0.48	0.03	3.6	0.6	0.22	0.18	0.40	5.00	92.00
P20	66.3	12.7	21.0	6.5	0.42	0.03	4.2	1.6	0.19	0.15	0.28	6.42	96.00
P21	64.3	14.7	21.0	6.8	0.42	0.03	4.6	1.4	0.18	0.16	0.12	6.46	98.00
P22	69.3	14.7	16.0	6.6	0.20	0.01	3.0	0.6	0.19	0.16	0.18	4.13	96.00
P23	61.3	15.7	23.0	7.2	0.48	0.03	4.0	0.6	0.20	0.18	0.0	4.98	100.00
P24	63.3	13.7	23.0	7.3	0.40	0.03	4.6	1.4	0.22	0.19	0.0	6.41	100.00
P25	53.3	24.7	22.0	6.8	0.66	0.05	4.4	1.6	0.20	0.14	0.10	6.44	98.00
Mean	62.66	17.34	20.00	6.84	0.50	0.03	4.98	1.29	0.21	0.18	0.15	6.85	97.12
Min.	53.30	9.70	10.00	6.20	0.20	0.10	2.40	0.40	0.17	0.14	0.00	3.91	92.00
Max.	69.30	34.70	26.00	8.00	1.06	0.09	18.00	2.40	0.27	0.25	0.40	20.96	100.00
Std.Dev	3.94	5.40	3.50	0.47	0.21	0.02	3.04	0.56	0.03	0.03	0.13	3.42	2.70
Coef. Var.	0.06	0.31	0.17	0.07	0.45	0.58	0.62	0.44	0.12	0.15	0.86	0.50	0.03

Org. C - organic carbon; BS - base saturation; TN - total nitrogen; Avail P - available phosphorus; ECEC - effective cation exchange capacity; min-minimum; max-maximum; std.dev- standard deviation; coef. var.-coefficient of variation



Table 2: Soil inorganic phosphorus fractions of the study area

Sample No. (P)	Total-P (mg/kg)	Bray's-P fraction (mg/kg)	Olsen-P fraction (mg/kg)
P1	61.25	4.25	0.72
P2	60	15.5	1.22
P3	98.75	4.25	1.2
P4	161.75	2.87	0.9
P5	53.75	3.75	1.5
P6	74.01	2.25	1.56
P7	258.75	2.5	2.29
P8	84.75	9.62	1.74
P9	87.5	2.87	1.28
P10	75.5	4.62	1.45
P11	153.75	4.62	2.28
P12	110.5	2.62	0.94
P13	117.5	2.37	1.14
P14	135.5	7.25	1.41
P15	57.5	3.5	0.8
P16	78.5	4.37	0.78
P17	82.5	6.12	1.54
P18	118.75	5.62	1.45
P19	75	8.37	0.74
P20	59	5.5	0.92
P21	161.75	3.12	1.56
P22	89.75	1.62	1.36
P23	60	1.12	0.8
P24	71	7.75	0.91
P25	60	4	1.2
Mean	97.89	4.82	1.27
Min.	53.75	1.12	0.72
Max.	258.75	15.50	2.92
Std. dev	47.24	3.09	0.43
Coef. var.	48.27	64.09	34.01

Min- minimum; max-maximum; std.dev- standard deviation; coef. var.-coefficient of variation

Sudano-Sahelian agroecological regions are mainly dominated by subsistence farming, food insecurity and extreme poverty because drylands are low productivity soils and traditionally unproductive because of frequent drought. The soil in the zone is characterized by low and irregular rainfall, high temperature, and low soil nutrient retention capacity. The native soil fertility is poor and unable to support high yield even with improved seeds. Irregular rainfall occasioned by climate change shortens the crop growing period. This study disclosed that most of the sampled fields were sandy loam, with low organic C, total N, and ECEC. The pH value was within the optimal ranges required for crop production. Despite that the soil had moderate to high base saturation contents values, and depleted base cations (Ca, Mg, K and Na). The status of soil phosphorus (P) fractions (total-P, Bray's-P and Olsen-P) were far below the critical levels. There is a need for adequate application of mineral fertilizers and organic inputs for a more productive soil.

Recommendation

The soil under study was found to be highly deficient in available (Bray) phosphorus, and this has a negative implication for crop production. The Olsen-P fraction was much less than the Bray's-P fraction. The mixed use of organic and inorganic P fertilizers is recommended to address this deficiency and improve the suitability of the soils for sustainable crop production.

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