

Phosphorus Dynamics and Their Relationship with Soil Properties in Soils of Tasawa Agricultural Project, Fazzan-Libya

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ABSTRACT

This study evaluates the influence of soil physicochemical properties on the distribution and dynamics of total phosphorus (TP) and available phosphorus (AP) in cultivated and uncultivated soils of the Tasawa agricultural project. Soil samples were collected from five cultivated circuits and three reference sites and analyzed for pH, electrical conductivity (EC), organic matter (OM), cation exchange capacity (CEC), soil texture, TP, and AP using standardized laboratory methods. Both cultivated and uncultivated soils exhibited slightly alkaline pH values (7.72–7.86), which provided a basis for interpreting other soil characteristics. EC was elevated in cultivated soils (234.44–311.15 mS/m) compared to reference soils (213.22 mS/m), suggesting increased ionic content associated with agricultural activity. OM content was also higher in cultivated soils (1.97–2.54%) than in reference soils (1.90%). CEC values were marginally lower in cultivated soils (18.35–20.60 meq/100 g) relative to the reference (21.39 meq/100 g). The soils were predominantly sandy (>82%), resulting in low nutrient retention and influencing phosphorus distribution. TP concentrations were higher in cultivated soils (36.99–96.00 mg/kg) than in reference soils (29.54 mg/kg). AP levels remained consistently low (1.95–4.49 mg/kg) across all samples, indicating substantial phosphorus fixation. Multivariate statistical analysis revealed significant positive correlations between OM and TP, sand and AP, and pH and AP. Principal component analysis (PCA) accounted for 72.93% of the total variance, identifying four principal components: soil texture, organic matter, mineral composition, and ionic environment. Cluster analysis confirmed the strong association between OM and TP, and emphasized the roles of soil texture and pH in determining phosphorus availability. Analysis of variance (ANOVA) indicated significant differences ($p < 0.05$) among soil properties and phosphorus forms, whereas EC did not differ significantly. In summary, phosphorus behaviour in these soils is governed by the interactions among soil texture, pH, and organic matter. These results highlight the complexity of phosphorus dynamics in sandy arid soils.

ديناميكيات الفوسفور وعلاقتها بخصائص التربة في مشروع تاسوا الزراعي، فزان، ليبيا

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المخلص	الكلمات المفتاحية
تقيم هذه الدراسة تأثير الخصائص الفيزيائية والكيميائية للتربة على توزيع وديناميكية الفوسفور الكلي (TP) والفوسفور المتاح (AP) في التربة المزروعة وغير المزروعة ضمن مشروع تاسوا الزراعي. جُمعت عينات التربة من خمس دوائر زراعية وثلاثة مواقع مرجعية، وُحلت لقياس درجة الحموضة (pH)، والتوصيل الكهربائي (EC)، والمادة العضوية (OM)، وسعة التبادل الكاتيوني (CEC)، ونسج التربة، ومحتوى الفوسفور الكلي، والفوسفور المتاح. كانت التربة المزروعة وغير المزروعة قليلة قليلاً (درجة الحموضة 7.72-7.86)، مما وفر سبباً لتفسير خصائص التربة الأخرى. كان التوصيل الكهربائي أعلى في التربة المزروعة (234.44-311.15 ملي سيمنز/متر) مقارنةً بالتربة المرجعية (213.22 ملي سيمنز/متر)، مما يشير إلى زيادة المحتوى الأيوني نتيجةً للزراعة. كما كان محتوى المادة العضوية أعلى في التربة المزروعة (1.97-2.54%) مقارنةً بالتربة المرجعية (1.90%). كانت قيم السعة التبادلية الكاتيونية (CEC) أقل قليلاً (18.35-20.60 ملي مكافئ/100 غرام) في التربة المزروعة مقارنةً بالتربة المرجعية (21.39 ملي مكافئ/100 غرام). وكانت التربة رملية في الغالب (>82%)، ذات قدرة منخفضة على الاحتفاظ بالعناصر الغذائية، مما أثر على توزيع الفوسفور. وكان تركيز الفوسفور الكلي (TP) أعلى في التربة المزروعة (36.99-96.00 ملغم/كغم) مقارنةً بالتربة المرجعية (29.54 ملغم/كغم). بينما ظلت مستويات الفوسفور المتاح (AP) منخفضة (1.95-4.49 ملغم/كغم) في جميع العينات، مما يشير إلى تثبيت قوي للفوسفور. وأظهر التحليل الإحصائي متعدد المتغيرات وجود ارتباطات إيجابية معنوية بين المادة العضوية والفوسفور الكلي، وبين الرمل والفوسفور المتاح، وبين الرقم الهيدروجيني والفوسفور المتاح. وفُسر تحليل المكونات الرئيسية (PCA) 72.93% من التباين الكلي، بأربعة مكونات رئيسية: نسج التربة، والمادة العضوية، والتركيب المعدني، والبيئة الأيونية. أكد تحليل التجميع وجود ارتباط وثيق بين المادة العضوية والفوسفور الكلي، وأبرز تأثير نسج التربة ودرجة حموضتها على توافر الفوسفور. وأظهر تحليل التباين وجود فروق دالة إحصائية ($p < 0.05$) بين	ديناميكيات الفوسفور الفوسفور المتاح إجمالي الفوسفور الزراعة فزان

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خصائص التربة وأشكال الفوسفور، بينما لم يكن للتوصيل الكهربائي أي تأثير دال. وخلصاً، فإن سلوك الفوسفور في هذه التربة ناتج عن تفاعلات بين نسيج التربة ودرجة حموضتها والمادة العضوية. وتؤكد هذه النتائج الطبيعة المعقدة لديناميكيات الفوسفور في التربة الرملية الجافة..

Introduction

Phosphorus (P) is an essential macronutrient that plays a critical role in plant growth and soil fertility; however, its behaviour in soil systems is highly complex due to strong interactions with soil physicochemical properties [1-3]. In many agricultural soils, particularly under intensive management, phosphorus tends to accumulate due to repeated fertiliser applications, while its availability to plants remains limited by fixation processes [4 - 8]. This imbalance can lead not only to reduced nutrient use efficiency but also to potential environmental risks associated with phosphorus enrichment. The dynamics of phosphorus in soil are strongly influenced by key factors such as soil pH, organic matter content, soil texture, microorganisms and cation exchange capacity [9 – 12]. In sandy and arid-region soils, these interactions become even more critical due to low nutrient retention capacity, high permeability, and reduced buffering potential. Under such conditions, phosphorus may either accumulate in stable forms or remain weakly available, depending on the combined influence of physical and chemical soil properties. Understanding the relationships between phosphorus forms and soil characteristics requires integrated analytical approaches. Multivariate statistical techniques, such as correlation analysis, principal component analysis (PCA), and cluster analysis (CA), provide powerful tools for identifying the dominant factors controlling phosphorus behaviour and for simplifying complex environmental datasets [13, 14]. Phosphorus management is vital in arid agricultural systems, yet few studies have thoroughly assessed its distribution and the effects of controlling factors using advanced statistical methods. Understanding these patterns is key to optimizing fertilizer use and maintaining productivity in these regions. Therefore, this study aims to

- (1) An assessment of total and available phosphorus in Tasawa project soils.
- (2) An Examination of the relationships between soil physicochemical properties and both total and available phosphorus using multivariate statistical analysis.

Materials and methods

Study area

The Tasawa agriculture project for the production and propagation of improved seeds is located in southern Libya, about 60 kilometers west of Murzuq, at a longitude of 13°25'00" E and a latitude of 26°10'00" N, and was established in 1999. It has 28 pivotal circuits at present, with a total area of about 1350 ha (Fig. 1)

Soil sampling

Soil samples were collected as described by [15] from five cultivated circuits, with five replicates per circuit. For each, about 1.0 kg of soil was collected at 0-30 cm depth using a soil auger sampler and placed in polyethene bags. Uncultivated control samples were collected from five nearby sites using the same method. All soil samples were dried at room temperature, sieved through a 2 mm sieve, and stored in plastic bags for analysis.

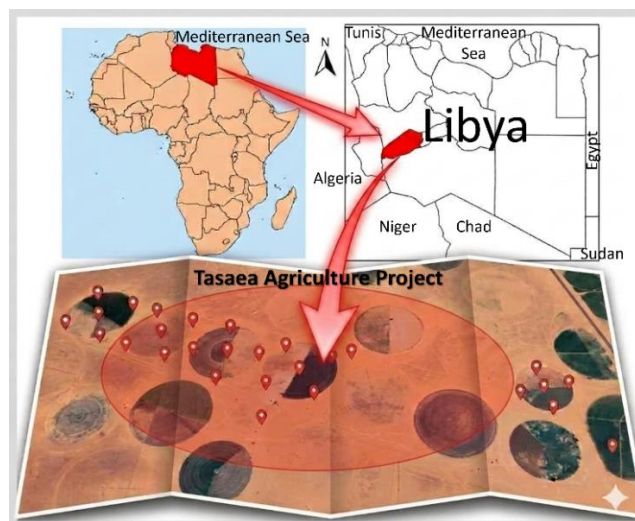


Figure 1:: Study area and sites of samples collection

Determination of physicochemical properties

Soil physical characteristics

pH

Soil pH was measured electrometrically using a JENWAY 3310 pH meter, adjusted by buffering solution pH 4.0, pH 7.0 and pH 9.0. Soil pH was measured using a 1:2.5 soil-to-water ratio [15] .

Electrical conductivity (EC)

The electrical conductivity (EC) was measured as described [16] using the conductivity meter (JENWAY 4310).

Organic Matter (OM)

The organic matter percentage (%OM) was determined as mentioned in [17].

Cation Exchange Capacity (CEC)

Cation exchange capacity was measured as mentioned by [18] using Flam photometer model 410 CORNING.

Soil texture (ST)

Soil texture was determined as described by [19].

Total phosphorus (TP)

The total phosphorus (available, soluble, mineral) in the soil measured spectrophotometrically as mentioned by [20], the concentration of total phosphorous assessed with spectrophotometer model JANYAA at 410 nm.

Available phosphorus (AP)

Determination of available phosphorus in soil samples was based on the method mentioned by [21].

Multivariate statistical analysis

SPSS v.25 was used to analyze the data.

Correlation coefficient

The correlation coefficient analysis estimates by using Pearson's coefficient (r) [23, 24]

Principal component analysis (PCA) and Factor analysis (FA)

Principal component analysis (PCA) is an effective statistical technique for simplifying complex data by transforming correlated variables into new, uncorrelated components. Its importance lies in reducing dimensionality while preserving most of the original variance, thus facilitating a deeper

understanding of the data structure and identifying the most influential factors [25, 26]. Factor analysis (FA) reduces the influence of less significant variables to create new, more streamlined variables based on the shifts achieved through principal component analysis (PCA)[25][26].

Cluster analysis (CA)

Cluster analysis (CA) aims to create meaningful groups (or clusters) of entities based on different related variables, such that the resulting clusters exhibit high internal homogeneity (intragroup similarity) and high external variance (intergroup differences). Hierarchical cumulative clustering is the most widely used cluster analysis method. In this study, Ward's method and squared Euclidean distances were used to measure similarity. This analysis helped identify the variance of physicochemical factors affecting total and available phosphorus concentration in the studied agricultural soils by forming smaller homogeneous clusters based on their internal correlations [27].

Analysis of Variance (ANOVA)

The analysis of variance is widely used across disciplines such as medicine, biology, psychology, engineering, and economics, and forms the backbone of experimental design and analysis in both research and applied settings [28]. The method relies on several key assumptions, including normality, independence, and homogeneity of variances, and can be extended to more complex designs such as two-way ANOVA, repeated measures, and mixed models [29]. The core logic of ANOVA is to partition the total variability observed in the data into components attributable to differences between groups (between-group variance) and differences within groups (within-group variance), and then to compare these using the F statistic [30].

Results and Discussion

Physicochemical Characteristics of Soil

Soil pH

The pH of the soil solution is an indication of the activity of hydrogen ions. The results of the soil pH are shown in (Table 1, Fig. 2). The pH values of C1, C2, C3, C4, and C5 ranged between 7.66 - 8.12, 7.68 - 7.98, 7.61 - 7.81, 7.59 - 7.99, and 7.65 - 7.96, with a mean \pm SD values of 7.86 ± 0.14 , 7.82 ± 0.10 , 7.72 ± 0.06 , 7.84 ± 0.12 , and 7.80 ± 0.10 , respectively. The results indicate low variation of pH in C1, C2, C4 and C5, whereas, the soil pH of C3 tending to be more acidity, which might be due to localized leaching of basic cations and higher organic matter decomposition that increases the release of organic acids [32, 33].

However, the pH of the reference soils ranged between 7.08 - 7.91 with a mean \pm SD of 7.61 ± 0.27 . The results show that the pH of the soil samples tends slightly toward alkalinity compared to the reference soil samples (virgin soil). The results indicate low standard deviation and variance values, while the reference samples show slightly higher values, which could be due to differences in soil texture and location. These results are similar to those reported [33]. The pH values do not have precise significance in agricultural practice [35, 36]. This finding contradicts with the results obtained [36], who identified a general relationship between pH and nutrient availability for crops, as well as selected environmental problems. Slightly alkaline and moderately alkaline soils (pH > 7.0) increasing the availability of Co, Cu, Fe, Mn and Zn, and also risk of ammonia volatilization, and

consequently cause an increasing of the availability of P and B. It has been reported that increasing of pH in soil can lead to the deficiency of P, due to the formation of insoluble Ca-phosphates [38, 39].

The tendency of cultivated soils to alkalinity might be due to basic minerals in the soil as Ca and Mg [39]. An addition of lime and/or calcium carbonate can raise the alkalinity of the acidic soil [41, 42]. On the other hand, Low rainfall, excessive use of alkaline fertilizers and irrigation with alkaline water can cause an accumulation of alkaline salts [42].

Table 1: Descriptive analysis of pH of the soil samples

	Circuit No. (n=15 for each circuit)					Reference soil (R)
	C1	C2	C3	C4	C5	
Min.	7.660	7.680	7.610	7.590	7.650	7.080
Max.	8.120	7.980	7.810	7.990	7.960	7.910
Mean	7.860	7.819	7.715	7.841	7.797	7.608
Std. D	0.138	0.098	0.060	0.118	0.095	0.273

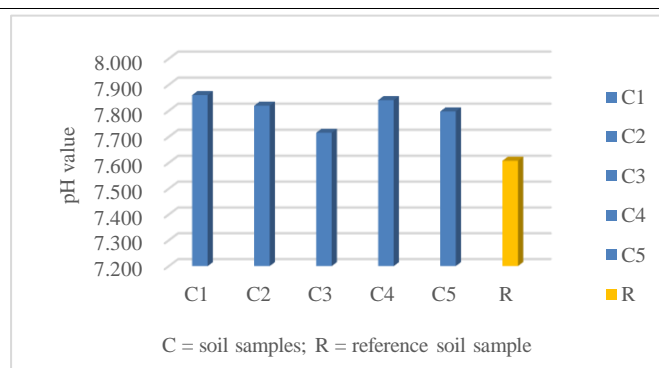


Figure 2:: Mean of pH of the soil samples

Electrical Conductivity (EC)

The EC results of the soil samples shown in (Table 2, Fig. 3). The EC of soil samples of C1, C2, C3, C4 and C5 were ranged between 171.35 - 643.8, 153.7 - 796.09, 150.71 - 383, 164.89 - 348.35 and 140.27 - 462.33 with a mean \pm SD of 311.15 ± 153.38 , 303.58 ± 220.2 , 234.83 ± 69.43 , 234.44 ± 61.39 , 291.31 ± 109.66 respectively. Whereas the EC of the reference soil samples ranged between 101.47 - 322.81 with a mean \pm SD of 213.22 ± 63.76 . The circuits of C1 and C2 show high value of EC compare to the C3, C4 and C5. The results exhibit a variation in the EC among the circuits and an increase of the EC of cultivated circuits comparing to the references soil samples. The variation of the EC in soil samples might be due to soil moisture, an addition of fertilizers, crops types, soil properties and/or the quality of the irrigation water [43].

Table 2: Descriptive analysis of EC (mS/m) of the soil samples

	Circuit No. (n=15 for each circuit)					Reference soil (R)
	C1	C2	C3	C4	C5	
Min.	171.35	153.7	150.71	164.89	140.27	101.47
Max.	643.8	796.09	383.00	348.35	462.33	322.81
Mean	311.15	303.58	234.83	234.44	291.31	213.22
Std. D	153.38	220.2	69.43	61.39	109.66	63.76

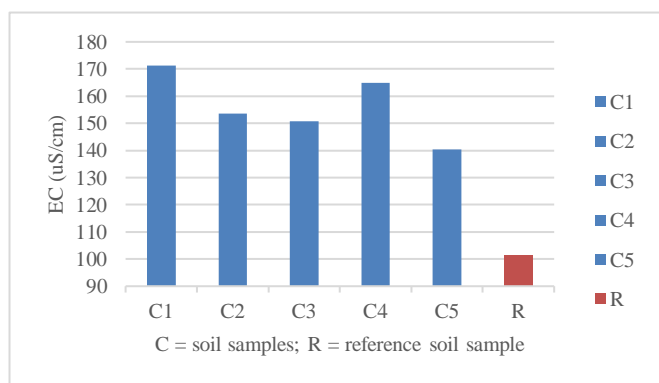


Figure 3:: Means of EC (mS/m) of the soil samples

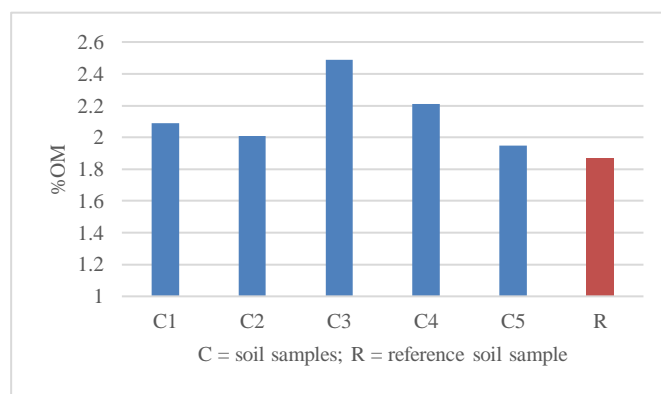


Figure 4:: Mean of organic matter (%OM) of the soil samples

Organic Matter (OM)

Soil organic matter is any material produced originally by living organisms (plant or animal) that is returned to the soil and goes through the decomposition process. The OM consists of a range of materials from the intact original tissues of plants and animals to the substantially decomposed mixture of materials known as humus [44] as show in (Table 3, Fig. 4). The OM of soil samples of C1, C2, C3, C4 and C5 ranged between 2.09 - 2.25, 2.01 - 2.07, 2.49 - 2.60, 2.21 - 2.32, and 1.95 - 1.99 with a mean \pm SD of 2.20 ± 0.05 , 2.04 ± 0.02 , 2.54 ± 0.04 , 2.26 ± 0.04 and 1.97 ± 0.01 respectively. Whereas the OM% of the reference soil samples ranged between 1.87 - 1.92 with a mean \pm SD of 1.9 ± 0.02 . The circuit C3 show high OM compare to C1, C2, C4 and C5, the differences of OM% might be due to the cultivation of this circuit with vegetables as we noticed during the soil sampling, however the other circuits were cultivated with different crops. It has been reported that variation in OM% might be due to no-tillage vegetable production tended to increase the more labile and more easily oxidizable organic matter fractions, mainly in the upper layers [46, 47]. All the cultivated circuits show high OM% compare to the uncultivated reference soil, that suppose due to the agriculture practices on the cultivated circuits, where the applying of organic fertilizer, compost or manure increase OM% levels significantly compared to uncultivated soils [47] and that can harbor higher microbial activity, contributing to more dynamic OM% turnover [49, 50], whereas the back incorporation of crops residues into the soil enhance OM% by providing a continuous organic materials input [50], the conservation practices like no-till and reduced tillage significantly reduce erosion and are more effective at preserving surface organic matter than traditional uncultivated soils [51] and Irrigation practices contribute to increased biomass production, thereby facilitating a greater return of organic material to the soil [53, 54].

Table 3: Descriptive analysis of organic matter (%OM) of the soil samples

	Circuits					Reference soil (R)
	C1	C2	C3	C4	C5	
Min.	2.09	2.01	2.49	2.21	1.95	1.87
Max.	2.25	2.07	2.60	2.32	1.99	1.92
Mean	2.20	2.04	2.54	2.26	1.97	1.90
Std. D	0.05	0.02	0.04	0.04	0.01	0.02

Cation Exchange Capacity (CEC)

The results in (Table 4, Fig. 5) showed that the CEC of the soil samples C1, C2, C3, C4 and C5 were ranged between 15.78 -22.57, 16.84 - 22.44, 16.72 -24.11, 17.31 - 23.76 and 16.37 -21.38 meq/100g soil, respectively, with a mean \pm SD of 18.37 ± 2.14 , 19.33 ± 1.78 , 20.6 ± 2.31 , 20.14 ± 1.84 and 18.35 ± 1.39 respectively. Where the reference CEC ranged between 19.19 - 23.76 meq/100g soil, with a mean \pm SD of 21.39 ± 1.4 . The soil of the cultivated circuits C1, C2, C3, C4 and C5 show slightly decrease in CEC comparing to the soil of the uncultivated sites, which could be due to the differences of OM, clay, soil texture and pH between the circuits. The main determinants of CEC are clay and organic matter; this is because both have a negative electric charge strong enough to attract the positively charged cationic elements [54].

Table 4: Descriptive analysis of CEC (meq/100g soil) of the soil samples

	Circuits					Reference soil (R)
	C1	C2	C3	C4	C5	
Min.	15.78	16.84	16.72	17.31	16.37	19.19
Max.	22.57	22.44	24.11	23.76	21.38	23.76
Mean	18.37	19.33	20.60	20.14	18.35	21.39
Std. D	2.14	1.78	2.31	1.84	1.39	1.4

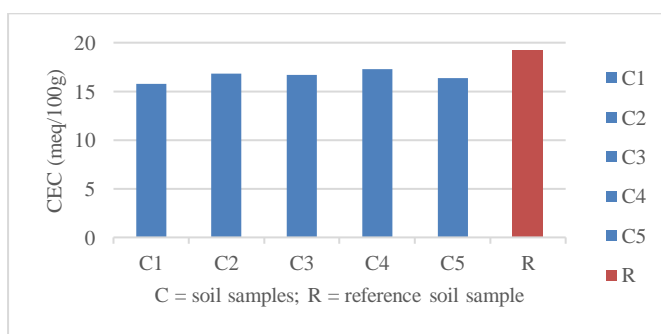


Figure 5: Mean of CEC of the soil samples

Soil Texture

The Mean value of sand content exceeds 82%, demonstrating uniformity in sand composition. According to the classification of soil texture suggested by United States department of agriculture [55], the soil can be considering sandy > 70% sand [56]. Sandy soil is low in organic matter, making it unsuitable for cultivation [58, 59]. Additionally, the study area is characterized by high porosity and large

spaces between particles, which facilitates water drainage. Furthermore, the absence of fine materials such as clay and silt prevent the soil from retaining nutrients and water, resulting in a rough and non-sticky texture typical of sandy soils [59]. The descriptive analysis of soil texture in (Table 5, Fig. 6) indicates that the percentage of sand in the soil samples of cultivated circuits ranged between 83.36 - 85.27%, whereas, the sand percentage of the uncultivated soils is 82.80%. The clay percentage in the soil of cultivated circuits are ranged between 8.07 - 11.93%, whereas, the clay percentage in uncultivated soil is 9.31%. However, the Silt percentage in the cultivated circuits soils ranged between 3.24 - 6.66%, whereas, in the uncultivated soils recorded 7.89%. The results indicate that the mean percentage of Silt in uncultivated soils is slightly higher than of the cultivated soils. The results indicate that the mean percentage of silt in uncultivated soils is slightly higher than in cultivated soils. These differences can be related to soil physical properties, especially soil organic matter (SOM) and associated structural changes.

Higher SOM in less-disturbed or reference soils is commonly linked with better aggregation and protection of fine particles (silt and clay), which promotes their retention in the surface layer [60].

Table 5: Descriptive analysis of soil texture (ST) of the soil samples

		Min.	Max.	Mean	Std. D.
C1	Silt %	5.26	7.29	6.29	0.94
	Clay %	9.72	10.76	10.35	0.5
	Sand %	81.97	84.01	83.36	0.82
C2	Silt %	6.24	8.28	6.66	0.84
	Clay %	7.86	8.86	8.07	0.41
	Sand %	83.85	85.89	85.27	0.83
C3	Silt %	4.26	7.29	6.48	1.22
	Clay %	9.3	10.33	9.52	0.42
	Sand %	83.4	85.41	83.99	0.82
C4	Silt %	5.26	7.29	5.88	0.84
	Clay %	7.91	9.95	9.32	0.84
	Sand %	83.8	85.8	84.8	0.66
C5	Silt %	2.21	5.27	3.24	1.15
	Clay %	11.64	12.8	11.93	0.45
	Sand %	82.98	86.15	84.83	1.26
Reference soil (R)	Silt %	7.29	8.3	7.89	0.51
	Clay %	8.88	9.94	9.31	0.52
	Sand %	82.76	82.84	82.8	0.03

Total Phosphorus (TP)

The results of total phosphorus in soil samples present in (Table 6, Figure 7), the TP in soil samples of C1, C2, C3, C4 and C5 were ranged between 86.97 – 105.68, 37.91 – 46.07, 53.52 - 65.04, 73.5 - 87.72 and 33.44 - 40.65 mg/kg. dwt, respectively, with a mean ± SD of 96 ± 5.35, 41.85 ± 2.33, 58.76 ± 3.49, 80.99 ± 4.37 and 36.99 ± 2.04 mg/kg. dwt,

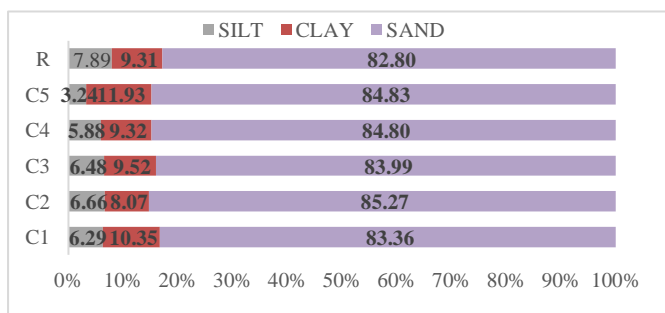


Figure 6: Mean of Soil texture (ST) of the soil samples

respectively, whereas the total phosphorus of the reference soil ranged between 26.76 - 32.53 with a mean ± SD of 29.54 ± 1.64. however, C1 and C4 circuits show high TP compare to C2, C3 and C5, which might be due the excessive use of P fertilizers, this is especially common in agricultural systems where fertilization exceeds the uptake capacity of plants, resulting in higher TP levels in the soil [61] and/or the presence of residues of organic materials that rich with phosphorus such as manure or compost, which are rich in phosphorus, can also contribute to elevated TP levels. These materials decompose slowly, releasing phosphorus over time, which accumulates in the soil [62]. The higher of TP in C1 and C4 is due to the leaching of phosphorus or its runoff caused by soil type, topography, or management practices in those circuits [63]. Higher TP levels can also result from soils with a greater capacity to adsorb phosphorus onto mineral surfaces, reducing its mobility and leading to accumulation **Error! Reference source not found.**

The reference soil (uncultivated) has the lowest TP value compare to the cultivated circuits highlighting the impact of human activities such as fertilization and organic material inputs on soil phosphorus levels. High TP values in cultivated soils have been reported in various studies. An elevated TP levels in soils under intensive crop production due to the excessive application of phosphorus fertilizers beyond crop requirements [65]. High TP levels were found in soils receiving long-term manure and compost applications, as reported by [66][66], this study emphasized the role of organic amendments in increasing soil phosphorus content.

Table 6: Descriptive analysis of TP (mg/kg) of the soil samples

	Circuit No. (N=15 for each circuit)					Reference soil (R)
	C1	C2	C3	C4	C5	
Min.	86.97	37.91	53.52	73.50	33.44	26.76
Max.	105.68	46.07	65.04	87.72	40.65	32.53
Mean	96.00	41.85	58.76	80.99	36.99	29.54
Std. D	5.35	2.33	3.49	4.37	2.04	1.64

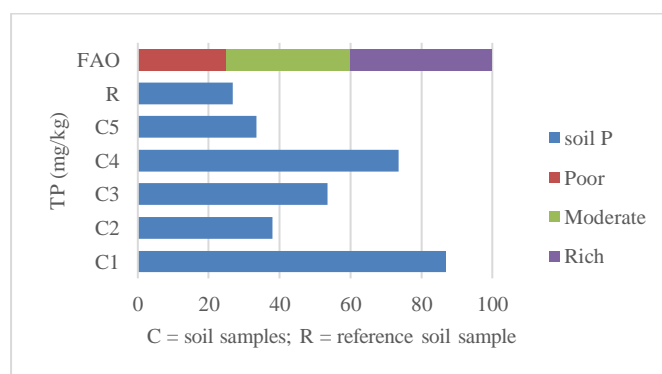


Figure 7: Mean of TP (mg/kg. dwt) of the soil samples

Available Phosphorus (AP)

The results in (Table 7, Fig. 8) showed that AP of soil samples of C1 and C3 were very poor with a mean of 2.89 ± 0.17 and 1.95 ± 0.07 (mg/kg) respectively, whereas C2, C4, and C5 were poor with a mean of 3.24 ± 0.14, 4.49 ± 0.20, and 3.17 ± 0.11 (mg/kg) respectively. The reference soil samples show very poor AP (2.28 ± 0.21 mg/kg. dwt).

The results of available phosphorus in soil samples present in (Table 7), the AP in soil samples of C1, C2, C3, C4 and C5

were ranged between 2.46 - 3.12, 3.01 - 3.44, 1.82 - 2.08, 4.22 - 4.95 and 3.01 - 3.35 with a mean \pm SD of 2.89 ± 0.17 , 3.24 ± 0.14 , 1.95 ± 0.07 , 4.49 ± 0.20 and 3.17 ± 0.11 respectively, whereas the available phosphorus of the reference soil ranged between 2.05 - 2.95 with a mean \pm SD of 2.28 ± 0.21 .

Table 7: Descriptive analysis of AP (mg/kg) of the soil samples

	Circuit No. (N=15 for each circuit)					Reference soil (R)
	C1	C2	C3	C4	C5	
Min.	2.46	3.01	1.82	4.22	3.01	2.05
Max.	3.12	3.44	2.08	4.95	3.35	2.95
Mean	2.89	3.24	1.95	4.49	3.17	2.28
Std. D	0.17	0.14	0.07	0.20	0.11	0.21

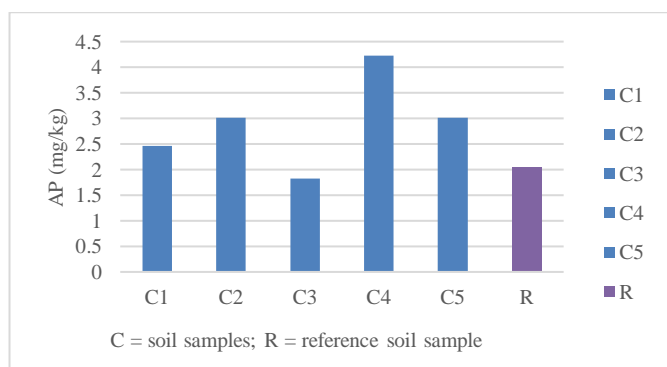


Figure 8: Mean of AP (mg/kg. dwt) of the soil samples

Multivariate Statistical Analysis

Correlation Analysis

The result in (Table 8) show strong positive correlation between the organic matter and the total phosphorus ($r = 0.555$, $p = 0.01$), where organic matter acts as a major source of phosphorus and enhance phosphorus retention and mineralization processes. This strong positive correlation indicates that total phosphorus increases markedly with increasing organic matter [67]. The results also showed positive correlation between the sand and the available phosphorus ($r = 0.457$, $p = 0.01$), although it is slightly below 0.50, this relationship is environmentally important where it is slightly below 0.5, it suggests that available phosphorus is higher in sandy soils, likely due to reduced P fixation compared to finer textured soils [68], and there are positive correlation between pH and available phosphorus ($r = 0.403$, $p = 0.01$) and between pH and total phosphorus ($r = 0.373$, $r = 0.01$) where higher pH values are associated with increased total phosphorus, reflecting improved P stability or accumulation under moderately alkaline conditions, and phosphorus availability increases with pH, consistent with reduced adsorption by Fe and Al oxides at higher pH [69]. The results showed strong negative correlations between silt and clay ($r = -0.712$, $p = 0.01$) and silt and sand ($r = -0.641$, $p = 0.01$), these correlations confirming that texture fractions are mutually exclusive, and there is negative correlation between pH and silt ($r = -0.333$, $p = 0.01$) which possibly reflecting depositional environments or pedogenic processes [70], and negative correlation between available phosphorus and silt ($r = -0.307$, 0.01) likely due to higher adsorption surfaces [71].

Principal Component Analysis (PCA) and Factor Analysis (FA)

The PCA approach identified four distinct components with eigenvalues exceeding 1.0 collectively represent 72.93% of the total variance as shown in (Table 9) and highlighting the primary physical, chemical, and organic drivers of phosphorus retention and mobility, while the FA reveals the conceptual factors that classify the physiochemical properties and phosphorus fractions which loaded in every PC as shown in (Table 11). The first principal component (PC1), which explains 28.34% of the variance and is strongly negatively loaded by Silt (-0.853), and strongly positively loaded by Sand (0.662), AP (0.643), and pH (0.625), represents the textural control of soil phosphorus retention (Silt and Sand). Higher silt

levels increase the specific surface area of soil particles, thereby enhancing phosphorus uptake and fixing it within the soil matrix. This component reflects the role of microparticles in regulating phosphorus storage and limiting its mobility. Overall, this factor represents a physical control on plant-available phosphorus, where soil texture and pH jointly influence P mobility [71]. The second principal component (PC2), explains 19.11% of the variance, dominated by a strong positive load of total phosphorus (0.816) and organic matter (0.750), indicating a component associated with phosphorus accumulation and storage, this component reflects the role of organic matter as a major phosphorus reservoir, contributing both to direct phosphorus input and enhancing its retention through complex formation and mineralization processes. Therefore, the PC2 represents a biogeochemical controlling factor for the total phosphorus stock, and is largely independent of soil texture. The third principal component (PC3) explained 14.00% of the variance, showing a strong negative loading of Clay (-0.732), indicating that this component reflects variability driven by clay mineral content and associated mineralogical properties rather than general soil texture.

The dominance of clay in this factor suggests that differences in clay mineralogy and surface reactivity exert a significant influence on nutrient retention processes. Higher clay contents are commonly associated with increased phosphorus fixation due to greater surface area, higher charge density, and stronger sorption capacity, leading to reduced phosphorus mobility and availability [68]. In contrast, soils with lower clay influence—typically coarser in nature—tend to exhibit weaker sorption mechanisms and comparatively higher phosphorus availability. Therefore, PC3 represents a mineralogical control on phosphorus retention, distinct from the broader particle-size distribution gradient represented by PC1, and highlights the role of clay-specific properties in regulating nutrient stabilization within the soil matrix. The fourth principal component (PC4) explaining 11.47% of the variance is positive loaded by EC (0.723) and CEC (0.590) this factor reflects the soil ionic environment influencing phosphorus retention and mobility. Higher EC indicates increased soluble ions, which can modify P adsorption through competitive interactions. Elevated CEC suggests greater surface charge and exchange sites capable of retaining phosphorus-associated cations (e.g., Ca^{2+} , Mg^{2+}), indirectly affecting P precipitation and stabilization [69].

Table 8: Correlation coefficient analysis of measured soil samples

	pH	EC	OM	CEC	Silt	Clay	Sand	TP	AP
pH	1								
EC	.134	1							
OM	.111	-.054	1						
CEC	.006	-.004	.085	1					
Silt	-.333**	-.125	.061	.284**	1				
Clay	.225*	.053	-.109	-.200	-.712**	1			
Sand	.227*	.120	.032	-.185	-.641**	-.082	1		
TP	.373**	.083	.555**	-.143	.006	.033	-.044	1	
AP	.403**	.052	-.120	-.144	-.307**	-.019	.457**	.364**	1

* Correlation is significant at the $p < 0.05$

** Correlation is significant at the $p < 0.01$

Table 9: Component analysis of measured soil properties

Comp.	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
Silt	2.551	28.340	28.340	2.551	28.340	28.340	1.949	21.652	21.652
Sand	1.720	19.113	47.453	1.720	19.113	47.453	1.852	20.583	42.234
AP	1.260	14.001	61.455	1.260	14.001	61.455	1.706	18.960	61.194
pH	1.033	11.474	72.928	1.033	11.474	72.928	1.056	11.735	72.928
TP	.914	10.161	83.089						
OM	.884	9.826	92.915						
Clay	.479	5.322	98.237						
EC	.159	1.763	100.000						
CEC	1.437E-6	1.596E-5	100.000						

Extraction Method: Principal Component Analysis.

Cluster Analysis (CA)

The result in (Fig. 9) show a dendrogram clearly illustrates two main clusters of variables based on their degree of similarity at rescaled distances. The first main Cluster A formed a tight, highly similar pair of variables at a very low rescaled distance containing OM and TP, this strong immediate linkage confirms a significant functional relationship between organic content and total phosphorus in the studied soils [72]. The second cluster (B) grouped the remaining variables, which further subdivided into three distinct subclusters, the first subcluster consisted of AP, Sand, and pH, showed relative similarity, indicating that phosphorus availability in the soil is strongly influenced by coarse texture and soil chemical conditions, where increased sand content reduces the soil's ability to fix phosphorus, while pH plays a pivotal role in phosphorus solubility and chemical reactions, particularly in alkaline soils [69]. The second subcluster was an isolated group containing only (EC), suggesting its behavior is distinct from the other physical and chemical properties, indicating a weak direct relationship between soil salinity and phosphorus forms in the studied soils, this suggests that the effect of EC on phosphorus-if any-is indirect and not a decisive factor in determining its distribution or availability. The third subcluster composed of clay, CEC, and silt, representing a strong correlation between basic physical properties and exchange properties that clustered at relatively higher distances, reflecting the role of these properties in fixing and retaining phosphorus on the surfaces of soil particles, this behavior is attributed to the high surface area of clay and high cation exchange capacity, which increases the soil's ability to absorb phosphorus and reduces its availability to plants [71].

These results are consistent with several previous studies indicating that total phosphorus is closely linked to organic matter, while its availability is related to soil texture and reactivity, and clay minerals contribute to its fixation within

the soil [73].

ANOVA Analysis

The results of the analysis of variance (ANOVA) in (Table 10) showed highly significant differences at the 95% significance level ($P = 0.05$) between the studied physicochemical properties, TP and AP. This variability coincided with statistically significant differences ($P < 0.05$) in the physicochemical properties affecting phosphorus mobility and availability in the soil, namely pH, organic matter (OM), cation exchange capacity (CEC), and soil

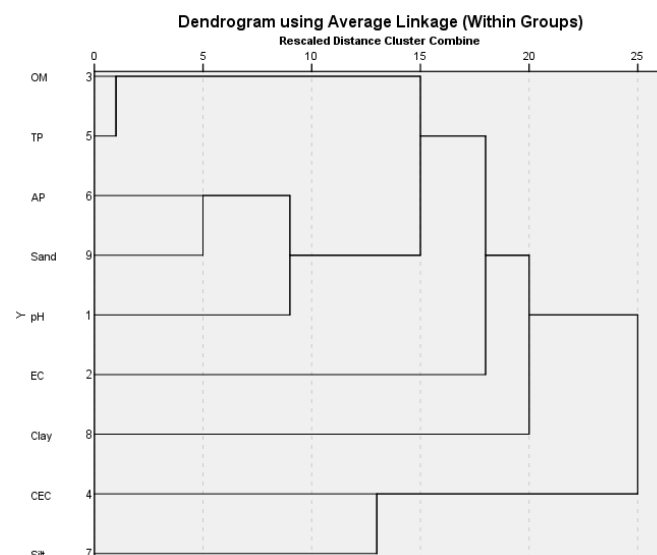


Figure 9: Dendrogram of measured soil properties and phosphorus forms

texture (sand, clay, and silt). The large variability in the values of available phosphorus ($F = 474.014$) and total phosphorus ($F = 868.502$) can be attributed to the close correlation between these values and the chemical properties

of the soil, where pH plays a pivotal role in determining phosphorus fixation and availability. Furthermore, the significant differences in organic matter content ($P = 0.000$) indicate its role in enhancing phosphorus availability by inhibiting fixation or through mineral decomposition, and the results showed significant variation in clay and silt content ($P = 0.000$), which directly affects phosphorus behavior. The soil's capacity to retain and fix phosphorus increases with increasing colloidal content (clay and organic matter) and cation exchange capacity (CEC), which also showed significant variation ($P = 0.000$). In contrast, the results showed no significant variation at the 95% significance level ($P = 0.157$) in electrical conductivity (EC) values, indicating that soil salinity in the studied locations was not a substantial factor influencing phosphorus behavior compared to other chemical and physical factors.

Table 10: ANOVA between soil properties and phosphorus (TP and AP) between circuits and within circuit ($p < 0.05$)

		Sum of Squares	df	Mean Square	F	Sig.
pH	Between Circuits	.682	5	.136	6.305	.000
	Within Circuits	1.816	84	.022		
	Total	2.497	89			
EC	Between Circuits	132537.068	5	26507.414	1.645	.157
	Within Circuits	1353666.498	84	16115.077		
	Total	1486203.566	89			
OM	Between Circuits	4.158	5	.832	822.290	.000
	Within Circuits	.085	84	.001		
	Total	4.243	89			
CEC	Between Circuits	114.181	5	22.836	6.740	.000
	Within Circuits	284.618	84	3.388		
	Total	398.798	89			
TP	Between Circuits	52248.926	5	10449.785	868.502	.000
	Within Circuits	1010.684	84	12.032		
	Total	53259.610	89			
AP	Between Circuits	59.092	5	11.818	474.014	.000
	Within Circuits	2.094	84	.025		
	Total	61.186	89			
Silt	Between Circuits	179.085	5	35.817	40.198	.000
	Within Circuits	74.844	84	.891		
	Total	253.929	89			
Clay	Between Circuits	125.792	5	25.158	85.444	.000
	Within Circuits	24.733	84	.294		
	Total	150.526	89			
Sand	Between Circuits	69.301	5	13.860	20.517	.000
	Within Circuits	56.747	84	.676		
	Total	126.048	89			

Conclusions

This study evaluates the physicochemical properties, total phosphorus (TP), and available phosphorus (AP) in soil samples from both cultivated and uncultivated areas of the Tasawa agriculture project. Comparative analysis revealed significant disparities in phosphorus levels, confirming that cultivated soils have accumulated more total phosphorus than uncultivated (virgin) soils. These findings identify phosphatic fertilizers and manure as the primary contributors to soil enrichment in the region. C1 and C2 exhibited the highest TP, with means of 96.00 and 80.99 mg/kg, respectively, while C2, C3, and C5 had means of 41.85, 58.76, and 36.99 mg/kg, respectively. The uncultivated soil sample had the lowest TP, with a mean of 29.54 mg/kg. For available phosphorus, AP concentrations varied among samples. C2, C4, and C5 had AP levels of 3.24, 4.49, and 3.17 mg/kg, respectively. According to the FAO classification, these soils possess poor AP content, whereas C1, C3, and the uncultivated soil are classified as having very poor AP content, with means of 2.89, 1.95, and 2.28 mg/kg, respectively. Strong positive correlations were observed between TP and OM, AP and Sand, TP and pH, AP and pH, pH and Clay, pH and Sand, CEC and Silt, and TP and AP. Strong negative correlations were found between Clay and Silt, Sand and Silt, pH and Silt, CEC and Clay, and AP and Silt. Principal component analysis explained 72.93% of the total variance. Factor analysis identified four components: PC1 (28.34%) included Silt, Sand, AP, and pH; PC2 (19.11%) included TP and OM; PC3 (14.00%) included Clay; and PC4 (11.47%) included EC and CEC. Cluster analysis revealed two main clusters: Cluster A included OM and TP, while Cluster B comprised three sub-clusters. The first sub-cluster included AP, Sand, and pH; the second, EC; and the third, Clay, CEC, and Silt. Analysis of variance (ANOVA) indicated no significant differences for EC (0.157 , $p < 0.05$) compared to other parameters. The remaining parameters showed significant differences at $p < 0.05$ between soil properties and phosphorus forms (0.000). These results suggest that OM is the primary factor in phosphorus accumulation and that pH influences phosphorus availability.

Recommendations

This study is carried out to assess the status of TP and AP in soil samples collected from Tasawa agricultural project, according to the results obtained in this research which indicated the accumulation of TP we can recommend the followings.

- Reduction of accumulated phosphorus by reducing the addition of phosphorus, by means of planting crops which can deplete the accumulated soil phosphorus.
- Improvement of phosphorus efficiency uptake by adopting microbial methods and biofertilizer techniques.
- Enhancement of soil quality and phosphorus availability by substituting organic fertilizers instead of chemical fertilizers.
- Investigating the effectiveness of phosphate solubilizing bacteria (PSB) as sustainable biological solution to mobilize the accumulated soil phosphorus.
- Monitoring the soil phosphorus fixation capacity to identify the specific mineralogical factors responsible for reduced phosphorus availability by conducting further researches.

- Improvement of soil health by approaching balances between the physicochemical properties through an adopting an integrated nutrient management, and multiple strategies for advanced remediation to maintain the soil sustainability.

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