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Article

Effects of Phosphate Fertilizers Management and Soil Texture On Some Growth Indicators and Economic Benefit of Sorghum Crop (*Sorghum bicolor L.*)

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Abstract: Sorghum is vital for Iraqi smallholder farmers and national food security. This study examined the impact of phosphate fertilizer levels and soil texture on sorghum (Sorghum bicolor L.) growth and economic returns. A pot experiment was conducted in Shatrah, Thi Qar Governorate, Iraq, during the 2022–2023 season used a randomized complete block design (RCBD) with three replicates. Four phosphate levels (0, 50, 100, 135 kg P_2O_5.ha^{-1}) and three soil textures (sandy loam, clay loam, clay) from different locations were tested. Sorghum seeds were planted in March 2023 with irrigation at 50% available water depletion. Experience data was analyzed statistically by using analysis of variance (ANOVA) with SPSS software. The optimal phosphate level (100 kg P_2O_5.ha^{-1}) significantly increased phosphorus concentration (0.145 g.kg^{-1}) and dry matter (26.08 g.pot^{-1}). Clay loam soil maximized dry matter (24.72 g.pot^{-1}), while sandy loam enhanced phosphorus concentration (0.140 g.kg^{-1}) and root length (28.47 cm). Root length negatively correlated with clay content (r = -0.67). The highest economic return (229.66 $. ha^{-1}) was achieved with 100 kg P_2O_5.ha^{-1} under clay loam, while 135 kg P_2O_5.ha^{-1} in clay soil had the lowest (3.70 $. ha^{-1}). Effective soil fertility management, tailored to soil texture, is essential not only for environmental protection , but also for boosting agricultural production .This study was carried out to determine the dose of phosphate fertilizers under different soil textures that would promote good availability that would promote good phosphate availability in soil solution to produce the best yield, economic profitability of sorghum fodder and introducing better fertilization practices among farmers in their agricultural investments.

Keywords: economic benefits, phosphorus accumulation, pot experiment, sandy loam, sorghum

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1. Introduction

In the midst of many crises between climate change and regional wars, the global population crisis raises its head as a warning to many problems, most notably food resources [1]. According to united nations projections, the world population is expected to reach 8.5–10 billion by 2050, a 34% increase [2], primarily in developing countries. To meet future dietary demands, food production must increase by over 70%, putting immense pressure on sustainable agricultural systems[3]. Before the covid-19 pandemic, 25.9% of the global population (2 billion people) faced moderate to severe food insecurity [4], and this trend is worsening. Government policies can mitigate food insecurity by investing in projects to boost cereal and fodder crop production and encouraging modern agricultural technologies. For example, the demand for animal feed is projected to reach 1,500 million tons by 2050 [5].

Crop production challenges often stem from environmental conditions and insufficient management practices, including fertilization[6]. Fertilization strategies must deliver nutrients precisely to match plant growth needs, enhance nutrient uptake, and prevent soil contamination. Plant productivity depends on nutrient availability in the soil solution, which facilitates root absorption [7]. However, arid and semi-arid regions suffer from declining soil fertility due to low organic and mineral nutrient content [8]. Phosphorus, a critical nutrient after nitrogen, as it makes up about 0.2% of a plant's dry weight and plays a key role in plant growth by supporting metabolic and physiological processes [9]. Phosphorus is essential in early crop growth stages, but its availability in soil is limited, the amount of total phosphorus in soil ranges from 100 to 2000 mg p kg-1 of soil, which represents approximately 350 to 7000 kg p. Ha-1 at a depth of 25 cm [10]. The amount of phosphorus used by crop ranges between 3 to 30 kg phosphorus ha-1, composing less than 0.1% of the total available phosphorus inside the soil [11], without effective soil management, phosphorus reserves are gradually depleted.so soil phosphoric analysis is critically important , as it plays a pivotal role in plant physiology and significantly influences crop yield .assessing soil quality prior to cultivation is essential to optimize nutrient availability and enhance agricultural productivity.

Furthermore, the soil factor is a second only to climate in terms of importance, as it acts as a natural medium for plant growth and provides mechanical support by giving the roots space to grow and develop [12]. Soil texture, a critical factor influencing agricultural productivity, impacts water retention, nutrient content, and plant growth.[13] defined soil texture, by the proportion of each sand, silt, affects physical and chemical properties, such as water-holding capacity and cation exchange capacity. These properties influence nutrient availability and agricultural sustainability [14].

Sorghum (*sorghum bicolor L.*) Has gained prominence as a fodder crop in arid and semi-arid regions due to its drought tolerance and adaptability to challenging conditions [15]. Unlike wheat, sorghum is not heavily imported, so production relies on local farmers to meet national needs. However, sorghum's high nutrient uptake can deplete soil resources without proper agricultural management. Effective phosphate fertilizer management, tailored to soil texture, is crucial for sustainable sorghum cultivation. Our study aimed to evaluate the management of phosphate fertilizers under different soil textures in order to reveal the soil requirements necessary for sorghum crop cultivation.

2. Materials and Methods

A. This Description of study area

The pot experiment was conducted in one of the orchards located in the shatrah district, thi- Qar governorate, which is located in southern of Iraq (360 km south of the capital, Baghdad). During the spring planting season 2022-2023 within the coordinates (2180328˚33′ n, 5218751˚44′ e), 34 m above sea level, aimed to study the effect of phosphate fertilizer management on some growth indicators and sorghum crop (*sorghum bicolor L.*) Economic benefit grown under different soil textures.

B. Soil sampling collection and preparation

The experiment was conducted using three different soil textures, sandy loam, clay loam and clay. Samples were collected by adopting the composite sampling method from different locations in thi-Qar governorate, Iraq and at a depth of 0-30 cm with exclusion of the 0–5 cm surface layer. The first sample from farms adjacent to the bada river, and was coded with (STSL), second sample from a farmer's field in al-rifai district, and was coded with (STCL), and the third sample from the shatrah district, was coded with (STC), and their locations are shown in (figure 1).

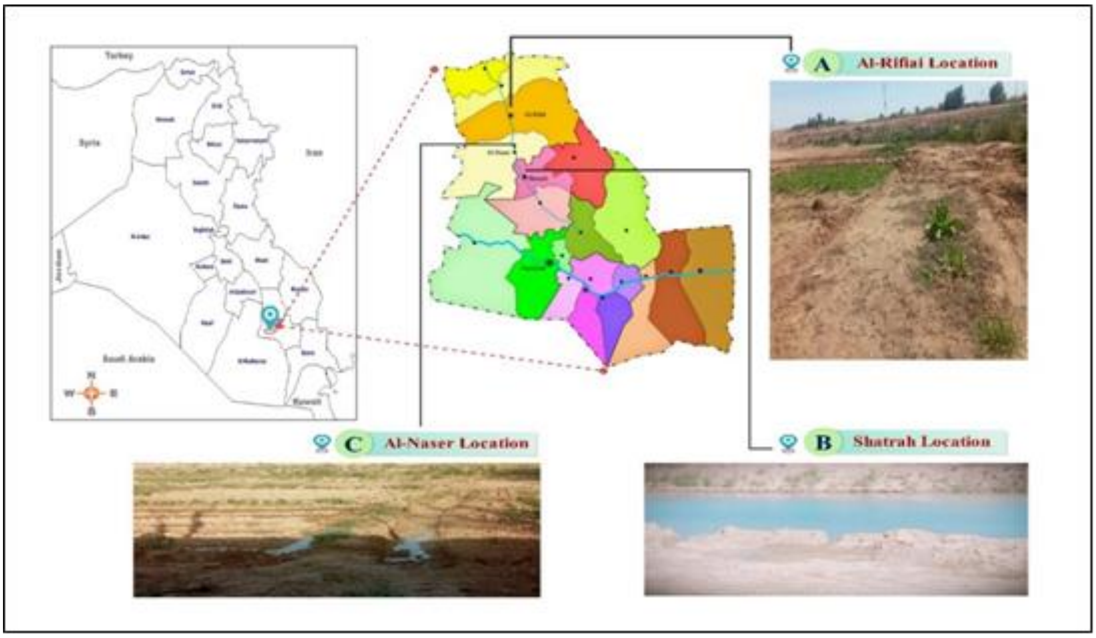

Figure 1. Map of the studied soil samples.

The soil was air dried, ground and passed through a sieve with 2 mm in diameter, then mixed and a sample was taken to conduct the soil physical and chemical analyzes before planting as shown in (table 1).

Table 1. Soil physical and chemical properties before sowing.

Sample site	ST	BD (Mg m-3)	AN (mg kg-1)	AP (mg kg-1)	AK (mg kg-1)
Al-Rifai	Clay Loam	1.14	120	18.5	35.9
Shatrah	Sandy loam	1.55	45	5.8	76.7
Al-Nasr	Clay	1.35	32	22	210

Note: ST, BD, AN, AP and AK are used to express soil texture, bulk density, available nitrogen, available phosphorus and available potassium respectively.

C. Pot experimental design and treatments

Pots experiment were conducted in a two-factorial Randomized complete block design (RCBD). The first factor included was with four different triple superphosphate (TSP) (46% P_2O_5) application rates were 0, 50, 100 and 135 kg P_2O_5 ha^{-1} respectively, mixed with and applied to soil of all treatments depending on elements concentration in each soil texture before sowing (Table 2). The second factor is soil textures, Using three different soil textures (Sandy loam, Clay Loam and Clay) respectively. An experimental unit consists of pot contains five kg of soil (top diameter of pot was 22.5 cm, base diameter of 16.5 cm and height of 18 cm) with a single plant in as shown in (Figure 2).

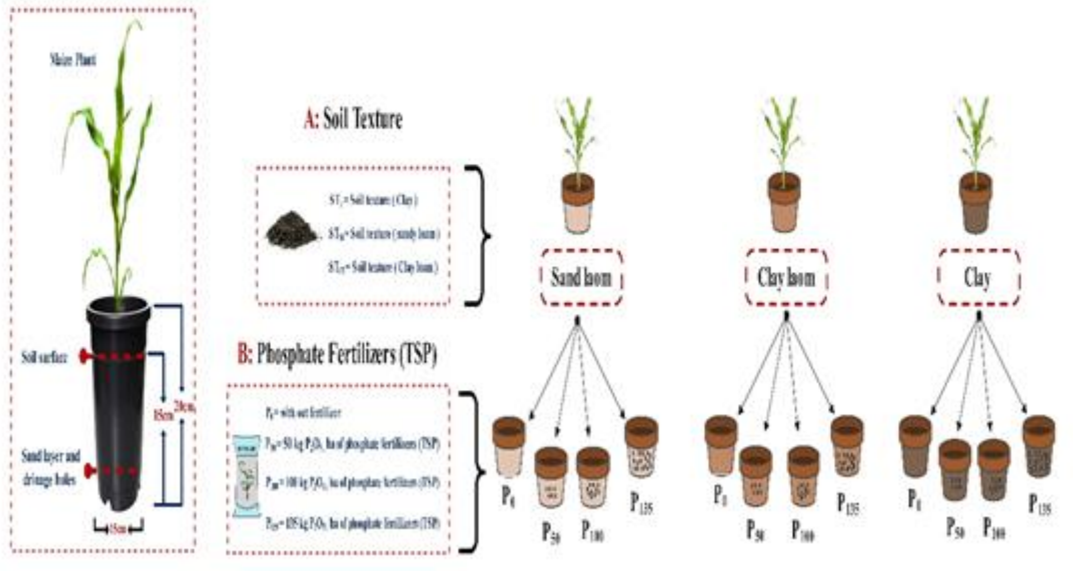

Figure 2. the diagram of pot experiment design. Each experimental transaction was repeated three times and repeater contained the interference between factor(A) and (B), the number of experiment units (N=36).

The applied rates of each fertilizer were dependent on crop requirements depending on the mentioned elements concentration in the soil solution before cultivation to compensate their deficiency under different soil textures (Table 2). Urea (46%N) as a form of nitrogen was applied at the same one level for all the treatments at a rate of 320 kg N ha^{-1} divided in two doses (at sowing, 15 days after sowing) [16], while Potassium (potassium sulfate) was applied at a rate of 80 kg K_2O ha^{-1} ten days after sowing .

Sorghum (*Sorghum bicolor L.*) Inkath variety was obtained from the Agricultural Research Center, Ministry of Science and Technology, Iraq. In 3rd week, March, 2023, three seeds per hole sown directly into each pot. After four leaves stage, each pot was thinned to one seedling with density plant of 53,333 plant. ha^{-1} [17]. All pots were irrigated using a drip irrigation system, depending on crop water requirement, taking into account the soil field capacity (FC, %), Before each irrigation process, a sample of pots soil from each experimental unit was taken at different depths depending on the plant growth stage to measure Soil water content.

Table 2. Fertilizer application rates under experimental treatments (g pot^{-1}).

Soil Texture	Fertilizers g pot-1				
	Urea	Triple superphosphate			Potassium Sulfate
		50	100	135	
Clay Loam	0.43	0.07	0.34	0.53	0.05
Sandy loam	1.25	0.21	0.48	0.67	0.42
Clay	1.39	0.03	0.30	0.494	without fertilizing

D. Laboratory analyses

1. Soil texture

Particles size distribution was measured using pipette and hydrometer methods according to [18].

2. **Bulk density**

The core sample method was used to estimate bulk density, as reported in [19].

3. **Available Nitrogen**

Modified alkaline permanganate method was used to estimate available nitrogen estimated by [20].

4. **Available phosphorus**

By using sodium bicarbonate ($NaHCO_3$) as an extractant, available phosphorus (Olsen P) was measured [21].

5. **Available potassium**

Ammonium acetate method was used to determine available potassium [21].

E. **Data collection**

1. **Total dry matter**

The average dry weight of the vegetative parts (leaves and stems) of each experimental unit was calculated by cutting and drying them at room temperature, then placing them in perforated paper bags in an electric oven at 65°C until the weight was constant, from which the total dry matter was estimated [22].

2. **Root dry matter**

Root samples were taken from each experimental unit (pot). Soil free by washing them with water, dried by hot oven at 65°C for 48 h until constant weight. After that, the dry root samples were weighed using a sensitive balance to obtain the dry weight [23].

F. **Statistical Analysis**

Experience data was analyzed statistically by using analysis of variance (ANOVA) at significance level of (L.S.D, $P \leq 0.05$) with SPSS software (version 22.0), The least significant difference (LSD) test was performed to find significant differences between treatment means. The GraphPad Prism software (GraphPad Prism version 9.0.0, 2020) package was used for making graphs.

G. **Economic Analysis**

The economic benefits of input data for sorghum forage production were evaluated using profitability analysis to evaluate the feasibility of phosphate fertilization under different soil textures according to the equation mentioned by [24].

Economic Benefit (EB) = (Yield with fertilizer× Market price) − (Yield without fertilizer ×Market price) − (Fertilizer cost× Amount of fertilizer applied)

Note: The price of sorghum feed and phosphate fertilizer were approved in US dollars, obtained from five agricultural supply stores in Thi Qar Governorate, Iraq, during the harvest stage.

A profitability analysis equation results were adjusted by using a modification factor (Table 3), for each type of soil texture, as shown by [25].

Adjusted Economic Benefit (AEB) = Economic Benefit ×Modification Factor

Table 3. Modification factor for various soil texture.

Soil Texture	Modification Factor
Sandy Loam	1.2
Clay Loam	1
Clay	0.8

3. Results

A. Influence of phosphorus and soil texture on fodder-yield related traits

Sorghum plants grown in the Untreated soils (without adding TSP) differed in their growth depending on the type of soil studied. Symptoms of phosphorus deficiency represented by purple color resulting from the accumulation of anthocyanin pigment in the leaf tissue, in addition to the small size of the growing plant in both Sandy loam and Clay Loam soils, because plant available phosphorus content was low (5.8 and 18.5 $mg.kg^{-1}$) compared to plants grown in clay soils. A significant ($p \leq 0.05$) effect of phosphorus and soil texture interaction was observed on plant growth characteristics in terms of dry biomass for shoot and root of Sorghum when grown under different levels of phosphorus fertilization in different soils texture.

Soil texture affects plant growth by influencing soil aeration, root penetration, water holding capacity, and availability of nutrients in the soil[26]. Data on total dry matter (TDM) of sorghum plants grown in three soil types revealed a significant effect of soil texture on this parameter. TDM production of shoots is a good indicator of economic yield and is therefore a suitable criterion for studying the growth response of plants at the seedling stage. It was observed from the data in (Figure 3), that there was an increase in TDM production by an estimated rate of 56 and 37%, respectively, in sorghum plants grown in clay soils compared to plants grown in unfertilized sandy loam and clay loam soils, as the weak production in those soils is due to the fact that the concentration of available phosphorus is very low and does not allow achieving optimal growth as in clay soils, and this is consistent with what was found [27]. The amount of TDM produced by plants grown in clayey loam soils continues to increase with the raising of phosphate fertilizer rates, especially when reaching the level of 50 kg $P_2O_5.ha^{-1}$, where dry matter production reached 21 $g.pot^{-1}$, but at this level an Significant increase in TDM production in plants grown in sandy loam soil, reaching 25 $g.pot^{-1}$ is observed. This is due to its coarse texture and low content of organic matter. In addition, sandy soil has a low capacity for exchanging cations (CEC), which reduces its ability to retain nutrients, including phosphorus. Therefore, any addition to phosphate fertilizers will directly address the problem of low phosphorus concentration in the *soil* solution, making the plant's response quick and giving the highest yield of the substance. While it was noted that there was a significant decrease in the production of TDM for plants in clay soils, recording 17 $g.pot^{-1}$. The reason for the decrease in the dry matter production may be attributed to the presence of clay minerals, which are characterized by an exposed surface area capable of absorbing phosphates from the soil solution after phosphate fertilizers addition , by exchanging with hydroxide ions (OH^-), thus making part of the phosphorus in the root zone depleted by the processes ofexchanging and fixation by soil minerals, which makes part of the roots out of reach of phosphorus [28]. However, with the increase in fertilizer application rates at 100 and 135 kg $P_2O_5.ha^{-1}$ in the sandy loam soil, this led to a significant decrease in TDM production compared to the clayey loam soil, that maintained plants growth continuity in it by increasing production of dry matter , given an increase of 34 and 53% compared to clay and sandy loam soils respectively . The decrease in TDM in sandy loam soils with increasing rates of phosphate fertilizers that leads to an increase in the available amount of phosphorus in the soil solution because of weak soil ability to hold it on and due to poor soil content of colloids which causes an imbalance sorption between the nutrients by plant in the soil solution, in addition, a portion of available phosphorus that is excess of the plant's need may be washed out beyond the boundaries of the root zone, which affects the production of TDM, and this is what was found by [29].

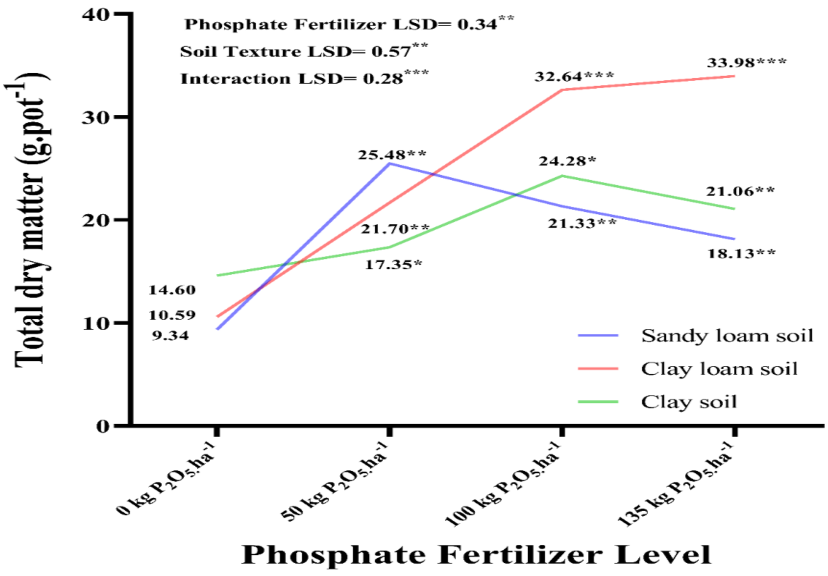

Figure 3. Phosphate fertilizer and soil texture effect on total dry matter production by sorghum.

Figure 4 and 6 show the changes in sorghum root lengths during the growing season, indicating differential stimulation of root growth by different phosphate treatments and soil texture. In particular, the control treatment (0 kg $P_2O_5.ha^{-1}$) in a sandy loam soil resulted in a 33% increase in root length compared to the highest fertilization level (135 kg $P_2O_5.ha^{-1}$), indicating that simple or no phosphorus application is more effective and gives the maximum root length. This is due to two reasons: either the original phosphorus content is sufficient for plant growth or it is due to the higher sand content which allowed the roots to explore more of the soil volume in search of nutrients with less physical resistance. However, this increase is at a certain fertilizer application level after which the added phosphate does not promote growth and overuse may reduce the effectiveness of the plant in rooting. However, root growth remained longer for plants growing in sandy loam soils, compared to clay loam and clay soils and under all levels of phosphate fertilizer addition. It is also noted in Figure 4 that clay loam soils require moderate levels of phosphorus to see an improvement in plant root lengths, most likely due to their rich clay mineral composition, which limits root expansion within the soil due to the high percentage of fine pores, which is reflected in its aeration and drainage of irrigation water, which is what our study reached through the negative correlation between root length values and clay content ($r = -0.67$, $p > 0.05$) Figure 5, indicating that with increasing clay content, root length tends to decrease. This is consistent with the results of[30], who observed limited root growth in soils with high clay content due to increased mechanical strength, which can prevent root penetration and nutrient uptake. The results of our study in Figure 4 showed that the plant grown in clayey soils gave a direct increase in root length with increasing levels of phosphorus fertilizer addition, recording its highest value of 25 cm compared to the control treatment. This may be due to the increased root growth in the surface layers without the other layers, since clayey soils are characterized by a high percentage of clay minerals that have specific surfaces capable of absorbing phosphorus (an element that is difficult to move inside the soil) from the soil solution on its surface. On the other hand, the reason may be attributed to the soil's ability to retain irrigation water, which helped increase root penetration into the soil in search of nutrients in the upper layers without other soil layers. This is consistent with what was found by [31].

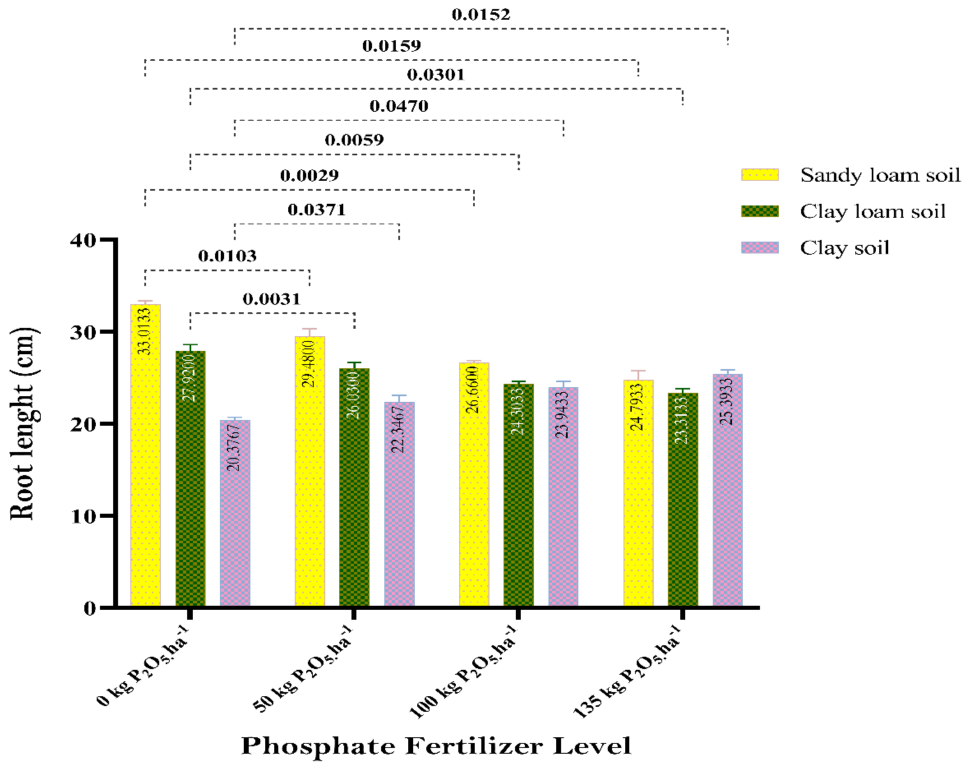

Figure 4. Phosphate fertilizer and soil texture effect on root length sorghum.

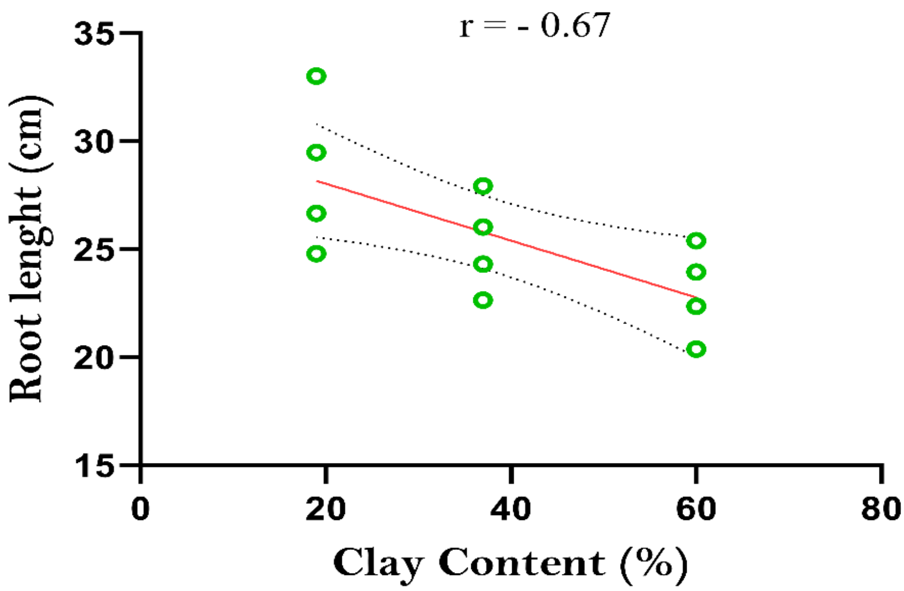

Figure 5. Correlation between sorghum's root length and clay contents.

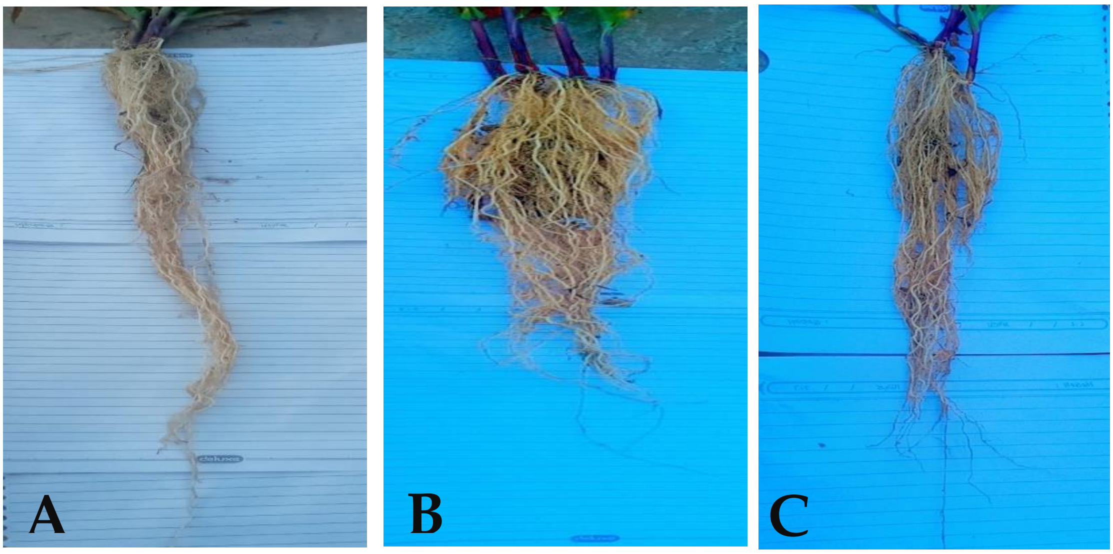

Figure 6. Root morphological changes in sorghum growth under different soil texture :(A) Sandy loam soil, (B) Clay loam soil, (C) Clay soil.

B. Phosphour accumulation in sorghum leaves

An increase in phosphate fertilization rates led to an increase in leaves 'phosphorus concentration, which is represented by the quantitative content of plant leaves, in all soil textures under study. This difference in phosphorus concentration between the three soils may be due to the difference in phosphorus availability and movement because of their different chemical and physical properties. A significant increase in phosphorus sorption appears when the added rate reaches 50 Kg P_2O_5.ha^{-1} in sandy loam and clay loam soils, where the phosphorus concentration in the leaves reached 0.133 and 0.119 g.kg^{-1}, respectively. The continuous increase in phosphorus concentration with increasing levels of added phosphate fertilizers, but the concentration of phosphorus in the leaves remains higher in plants cultured in a sandy loam texture compared to clay loam soil, reaching 0.163 and 0.151 g.kg^{-1} respectively ,when the level of phosphorus is added 100 Kg P_2O_5.ha^{-1}. However, increasing the level of phosphate fertilizer applied to the soil at 135 Kg P_2O_5.ha^{-1} is subject to a decrease in the concentration of phosphorus absorbed in sorghum leaves, but it always remains higher than the levels of 0 and 50 Kg P_2O_5.ha^{-1}, respectively. which agrees with [32] observed that the leaf phosphorus concentration in leaves of potatoes grown in sandy soil was higher than in potatoes grown in clay soil with an increase in phosphorus supply, possibly due to the relatively higher increase in phosphorus availability in sandy soil compared to clay soil. Thus, because phosphorus is more available in sandy soils, where uptake by soil colloids is lower, the potato plants likely absorbed more phosphorus from these soils, resulting in a higher leaves concentration than in clay soils. The leaf phosphorus concentration was within the optimal range for potato plant growth, which is 2.5 to 5.0 g. kg^{-1}, when fertilized at rates higher than 100 Kg P_2O_5.ha^{-1} in sandy soil [33]. Accoding to our study results ,for clay soil the plant responded directly to phosphate fertilization at a fertilization level of 100 Kg P_2O_5.ha^{-1}, so that the phosphorus concentration in the leaves reached 0.121 g.kg^{-1} (compared to the control treatment), then decreased to a concentration of 0.095 g.kg^{-1} at the level of 135 Kg P_2O_5.ha^{-1}, but it remains higher than what it is under the level of 50 Kg P_2O_5.ha^{-1} and the comparison treatment.

Table 4. Effect of phosphate fertilizer rate and soil texture on phosphor accumulation in sorghum leaves at harvest.

P rates	Soil Texture			Mean
	Sandy Loam	Clay Loam	Clay	
Control	0.120	0.100	0.046	0.088
50	0.133	0.119	0.079	0.110
100	0.163	0.151	0.121	0.145
135	0.147	0.130	0.095	0.124
Mean	0.140	0.125	0.085	-

LSD0.05 for P level	LSD0.05 for Soil Texture	LSD0.05 for Interaction
0.335	0.500	0.210

Note: P rates: phosphate fertilizer rate.

4. Discussion

A. Economic benefit

Economic benefit is a critical consideration in agricultural production, linking input costs to revenues from increased yield. Forage productivity and economic returns are significantly affected by phosphate fertilizer, its effectiveness is related to soil texture due to differences in nutrient retention and plant uptake efficiency. Table 5 showed that Sandy Loam Soil had the highest economic benefit at 50 kg P_2O_5.ha^{-1} (145.88 $. ha^{-1}), but the return sharply decreased as phosphorus application increased. At 100 kg P_2O_5.ha^{-1}, the economic benefit dropped to 59.19 $ ha^{-1}, and at 135 kg P_2O_5.ha^{-1}, it fell further to just 4. 63$.ha^{-1}. This indicates that the optimal phosphate fertilization for sandy soils is closer to 50 kg P_2O_5.ha^{-1}, as phosphorus inputs initially led to an increase in dry matter production, which was reflected by the economic return. This is explained by the nutrients availability in soil's solution, making them easier to absorb by the plant. This leads to a decrease in the cost of fodder production and an improvement in terms of quantity and quality, which will later be reflected in an improvement in financial gains. However, these returns decreased with increasing levels of phosphorus applied to these soils, as phosphorus will be exposed to washing process outside the limits of plant benefit [34], which makes the cost of additional phosphate fertilizers exceed their benefits in terms of return. In this case, this is what was observed in the study [35].

The clay loam soils showed a more favorable economic scenario, with an increase in economic benefit from 133.70 $. ha^{-1} at 50 kg P_2O_5.ha^{-1} to 229. 66$.ha^{-1} at 100 kg P_2O_5.ha^{-1}. Even at 135 kg P_2O_5.ha^{-1}, the economic benefit remained relatively high (213.26 $. ha^{-1}), although slightly reduced. This suggests that clay loam soils respond well to phosphorus fertilization due to their balanced soil particle texture and better ability to retain nutrients against soil loss and availability when needed by the plant, which will be reflected in both yield and economic returns at moderate levels of phosphorus, as confirmed by [36]. The relatively high economic returns at 100 kg P_2O_5.ha^{-1} suggest that this level of phosphorus is likely optimal for maximizing both yield and profitability in clay loam soils, and this is consistent with recent studies, such as that by [37] which support our results in this soil texture type by showing that moderate phosphate levels increase productivity and economic returns in clay loam soils.

Conversely, clay soils achieved a modest economic benefit at 50 kg P_2O_5.ha^{-1} (38.23$. ha-1), which increased to 92.32 $. ha^{-1} at 100 kg P_2O_5.ha^{-1}. However, the economic return dropped sharply to only 3.70 $. ha^{-1} at 135 kg P_2O_5.ha^{-1}. This suggests that despite the positive yield response up to 100 kg P_2O_5.ha^{-1}, adding higher phosphor level to clay becomes economically unfeasible, likely due to the limited capacity of these soils to use phosphorus effectively at higher levels. High phosphorus application rates may lead to nutritional imbalance or may be subject to fixation within soil layers , and thus will limit the plant's phosphorus absorption from the soil solution, which increases the effort exerted by the plant to obtain it, which is reflected in the yield, and this would reduce the efficiency of the added phosphate fertilizers in addition to the economic return, as indicated by [38].

These results emphasize the need for scientific management strategies of phosphate fertilizers that are specifically designed to balance agricultural benefits and economic profitability, especially by avoiding excess fertilizers use in soils with limited response to phosphorus by using techniques that ensure the availability of phosphate in such soils, such as the technique of adding strip fertilizers or using phosphate soluble fertilizer and giving them according to studied methods following the plant specific recommendations in order to ensure greater effectiveness in terms of economic cost, as indicated by [39].

Table 5. Economic returns of dry matter production for sorghum affected by phosphate fertilizer rates added to different soils textures.

Soil texture	**P rates**	**Dry matter yield Kg. ha-1**	**Economic Benefit $. ha-1**
Sandy Loam	50	1350.44	145.88
	100	1130.31	59.19
	135	2409.19	4.63
Clay Loam	50	960.71	133.70
	100	1729.74	229.66
	135	1800.94	213.26
Clay	50	919.37	38.23
	100	1286.66	92.32
	135	1116.08	3.70

Note: P rates: phosphate fertilizer rate

5. Conclusion

Phosphorus plays a crucial role in many physiological processes within plants, such as energy transfer, genetic inheritance, protein synthesis, and cell division. In addition, it is essential for promoting root growth, enhancing stem structural integrity, and influencing key reproductive stages such as flowering, fruiting, seed development, and crop maturity. Therefore, effective management of P according to different soil types is crucial to improve crop growth, reduce production costs, and mitigate environmental risks caused by fertilizer use. Our study shows that soil texture significantly affects phosphorus availability and biomass production, with clayey soils (high clay content) exhibiting lower biomass production due to poor root growth and limited phosphorus availability in the topsoil, likely due to the high phosphorus fixation capacity of these soils and the low availability of phosphorus in the soil solution. This low availability of phosphorus is supported by the strong negative correlation ($r = -0.67$) between root dry matter production and clay content, indicating that poor root growth in heavy clay soils is directly related to reduced phosphorus uptake. Conversely, soils with a clayey loam texture showed better growth and biomass production, suggesting that these soils provide more favorable conditions for root growth and phosphorus uptake. These results emphasize the importance of targeted phosphate fertilization strategies based on soil, plant, and environmental factors, especially for soils with high clay content and especially in the case of limited arable soils, where improving phosphorus availability through strategic fertilization or soil amendments can enhance nutrient uptake and improve sustainable crop production, reduce high fertilizer inputs, and maximize yields and ultimate economic returns to the farmer.

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