

Effect of Salinity on Inorganic Phosphorus Fixation in Sara and Bajoa Soil Series of Ganges Tidal Floodplains

Abstract

Soil salinity significantly impacts nutrient availability, especially phosphorus (P), in the southwestern regions of Bangladesh, where salinity is prevalent during the dry season. This study investigates the effect of varying salinity levels (2, 4, 8, and 12 dS m⁻¹) on phosphorus transformation and availability in two soil series, Bajoa and Sara, from the Ganges Floodplain. A laboratory incubation experiment was conducted with samples exposed to the salinity treatments over 0, 15, 30, and 60 days, followed by sequential extraction to quantify the phosphorus fractions. Results indicated that increased salinity led to a shift in phosphorus forms, with calcium-bound phosphorus (Ca-P) dominating over iron and aluminum-bound (Fe, Al-P) and reductant-soluble phosphorus (Rs-P) in both soil series. The Bajoa and Sara soils showed distinct responses, with a consistent reduction in bioavailable P as salinity levels increased. This fixation of phosphorus into less accessible forms has critical implications for nutrient management, as reduced P availability could limit crop productivity in saline soils. The study highlights the need for targeted phosphorus management strategies for saline-affected soils, emphasizing the importance of tailored fertilization practices to enhance sustainable agricultural productivity. Further research should explore adaptive management practices for phosphorus fertilization to mitigate the adverse effects of salinity on nutrient dynamics in affected regions.

Keywords: Phosphorus, nutrient availability, Sara series, Bajoa series, soil salinity, phosphate sorption.

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Introduction:

Soil salinity poses a significant agricultural challenge in the southwestern regions of Bangladesh, notably in Khulna, Satkhira, and the Sundarbans, where salinity increases sharply during the dry season. This salinity not only impacts soil properties but also restricts the availability of key nutrients, particularly phosphorus—a critical macronutrient second only to nitrogen in its importance for plant health and productivity. Despite its abundance, a large portion of soil phosphorus exists in forms that are difficult for plants to absorb due to soil salinity creates an osmotic imbalance, making it challenging for plants to absorb water and nutrients, including phosphorus (Teshale, 2023). Additionally, high salt concentrations can lead to the fixation of phosphorus in forms that are less accessible to plants, particularly in alkaline and calcareous soils (Muindi, 2019) (Phosphorus Management in Salt Affected Soil - A Review, 2023). This nutrient limitation can severely impact crop yields and soil fertility, posing further challenges for sustainable agriculture in these regions. The Bajoa and Sara soil series, located within the Ganges Floodplain, were selected for this study due to their distinct characteristics and current agricultural use whereas the Bajoa soil series is characterized by poor drainage and high salinity due to seasonal flooding, making them less suitable for diverse crops beyond rice (Rahman *et al.*, 2023; Singh *et al.*, 2021). In contrast, Sara soils, found on gently rolling ridges, are used for a variety of crops, including vegetables, by both individual farmers and local communities. These soils support a variety of crops, including vegetables, which are essential for local communities' nutrition and livelihoods (Banya *et al.*, 2019). Many farmers in these regions lack effective management techniques for salt-affected soils, which exacerbates the decline in rice production (Omar *et al.*, 2022). These soils are particularly relevant for studying nutrient dynamics due to their vulnerability to salinity, which affects nutrient availability and uptake (Fageria *et al.*, 2011). The transformation of phosphorus in saline conditions can significantly impact plant growth, making these soils

critical for research on nutrient management strategies (Bhardwaj *et al.*, 2016). The choice of these soils is motivated by their agricultural importance and their vulnerability to salt-induced phosphorus transformation, making them suitable candidates for understanding nutrient dynamics in saline environments.

Next to nitrogen, phosphorus (P) is the second most important macronutrient as an essential plant nutrient. It is a key nutrient for higher and sustained agricultural productivity (Duputelet *et al.*, 2013). Phosphorus is a vital mineral for biological functions and structural integrity in both plants and animals. In plants, it plays a crucial role in cell division and the development of growing tips. Inorganic phosphorus (Pi) occurs mainly as H_2PO_4^- and HPO_4^{2-} adsorbed onto the surfaces of oxides and hydroxides of Fe or Al, organic matter or bound to Ca. The adsorption of P in soils depends on soil pH and clay minerals (McBeath *et al.*, 2005). Although soils may contain hundreds to thousands of kilograms of phosphate per hectare, much of this phosphate is often unavailable to plants. The processes of adsorption, desorption, and precipitation in the soil regulate phosphorus availability (Sims *et al.*, 2000). Phosphorus sorption isotherms, which relate the concentration of phosphorus in soil solution to the amount sorbed by the soil, are useful tools for accurately predicting crop phosphorus fertilizer needs (Amarh, 2021). These isotherms help assess optimal phosphorus levels for various crops and soils (Saeed *et al.*, 2021). A key factor limiting phosphorus availability is its fixation by iron, aluminum, and calcium in the soil (McBeath *et al.*, 2005), with up to 70-90% of phosphorus in the soil becoming fixed and difficult for plants to absorb. As a result, phosphorus deficiency reduces crop productivity by 30-40% (Vance *et al.*, 2003), especially in calcareous soils and arid regions where salinity is a problem. Salt stress affects soil conditions like electrical conductivity (EC), sodium adsorption ratio (SAR), pH, structure, and aeration, further limiting phosphorus availability. Phosphorus bioavailability is more restricted in salt-affected soils compared to normal soils (Qadir *et al.*, 2005).

Providing adequate P to plants can be difficult, especially in calcareous soil. In calcareous soils, inorganic phosphorus fractions are categorized into iron, aluminum-bound phosphate, reductant-soluble phosphate, and calcium-bound phosphate, with methods varying due to separation difficulties. Phosphorus exists in soils in several forms, and understanding its different geochemical fractions is crucial for assessing long-term phosphorus availability. Yanhong *et al.* (2014) and Silija *et al.* (2013) suggested that sequential extraction methods like the Hedley technique accurately determine bioavailable P fractions, aiding in soil fertility, ecosystem productivity, agricultural runoff management, and water body eutrophication prevention. The bioavailability of phosphate in soils is influenced by soil pH. Acidic soil has reduced P solubility, improving with neutrality. Alkaline soil experiences reduced availability due to P reacting with calcium, with the lowest solubility at pH 8. Lime presence exacerbates this issue thus low P solubility in calcareous soil leads to poor fertilizer efficiency, stunting plants with shortened internodes and poor root systems, and yield loss without visible symptoms. Applying phosphorus fertilizer at standard rates using conventional methods may not always lead to the best yield or crop quality (Stark and Westermann, 2003). This study hypothesizes that increased soil salinity will reduce the availability of bioavailable phosphorus in the Bajoa and Sara soil series, primarily through changes in inorganic phosphorus fractions. By analyzing phosphorus transformations under different salinity treatments, this research seeks to contribute to a better understanding of phosphorus dynamics in saline soils, supporting improved nutrient management strategies for the sustainable use of salt-affected lands in Bangladesh. The findings aim to inform practices that could optimize phosphorus fertilization, thereby enhancing productivity and promoting sustainable agriculture in the region.

Materials and Methods

A laboratory incubation experiment was conducted using two soil types from the Ganges Floodplain to investigate the impact of salinity on the fractions and availability of inorganic phosphorus.

General Information of Studied Soil Series

Bajoa series

The Bajoa series, which are formed in a tidal floodplain basin, undergo seasonal shallow to moderate deep flooding. These soils, which are poorly drained, originate from tidal deposits. The subsoil consists of grey to olive-grey silty clay loam with a blocky structure that ranges from moderate to strong in the B horizon. They are classified into five phases: highland, non-saline medium highland, saline medium highland, medium lowland, and medium lowland with flood risk (Rahman, 2004). Additionally, Sarker *et al.* (2024) found that the phosphate sorption capacity of this soil is relatively low.

Sara series

The Sara series, formed in the levee deposit, are found from the tops to the middle of gently rolling ridges. They experience intermittent to shallow flooding and have imperfect to poor drainage. The soil is a light olive-brown to olive calcareous silt loam, typically with a weak prismatic and sub-angular blocky structure in the B horizon (Rahman, 2005).

Some Physical and Chemical Analysis of Soils

The physical and chemical properties of the soils were measured three times using conventional methods. One of the popular methods, the hydrometer method, as explained by Day (1965), was used to analyze the particle size of the soils. Marshall's Triangular coordinate system determined textural classes by fitting the values for % sand, % silt, and % clay. The

pH of the soil was measured electrochemically using a glass electrode pH meter, with a soil-to-water ratio of 1:2.5, as recommended by Jackson (1962). The soil's electrical conductivity (EC) was measured using a soil-to-water ratio of 1:5 with an EC meter, then converted to a 1:1 ratio following USDA (2004) guidelines. The EC (Soil: Water =1:5) value was determined by an EC meter (USSLS, 1954). The soil organic carbon was measured using Walkley and Black's wet oxidation method (Walkley & Black 1934). The organic matter was calculated by multiplying the organic carbon percentage by the conversion factor of 1.724. The cation exchange capacity (CEC) of the soil was measured by the flame photometric method as described by Jackson (1962). Soil samples were digested using a mixture of HNO₃ and HClO₄ in a 2:1 ratio, following the procedure described by Jackson (1973), to determine total phosphorus (P). The total phosphorus content in the soil was analyzed using the vanadate-molybdate yellow color method, on the other hand, the total nitrogen of the sample was measured using the micro Kjeldahl method, as outlined by Jackson (1973).

Incubation Experiment

An incubation experiment was carried out on the effect of saline water treatments on inorganic phosphorus fractions and the availability of the two different soil series at field capacity moisture conditions. The salinity treatments were 2 dSm⁻¹, 4 dSm⁻¹, 8 dSm⁻¹ and 12 dSm⁻¹. A 100g soil sample was incubated in a 500 ml plastic container, and sealed with parafilm to reduce water loss. The oven-dry weight of the soil was measured gravimetrically, and samples were collected at 0, 30, and 60 days to study the transformation of various forms of inorganic phosphorus.

Table 1: Name of treatment code

Treatment's code	Treatments
	EC (dS m ⁻¹)
T ₁	2
T ₂	4
T ₃	8
T ₄	12

Table 2: Some physical-chemical characteristics

Properties	Sara soil series	Bajoa soil series
Texture	Silt loam	Silty clay loam
Sand (%)	25	8
Silt (%)	56	62
Clay (%)	20	30
pH	7.57	6.97
EC (dS m ⁻¹)	1.56	2.35
CEC (cmol kg ⁻¹)	23.30	20.46
Organic C (%)	1.22	9.96
Organic matter (%)	2.10	17.17

Methods for Fractionation of Inorganic Phosphorus

Inorganic phosphorus fractions were determined using the methods outlined originally by Chang and Jackson (1957). The current investigation adopted modifications as reported by Kuo (1996). In their original fractionation scheme, Chang and Jackson (1957) proposed six inorganic-P fractions of soil. The fractionation procedure of Chang and Jackson (1957) was modified in two stages as suggested by Peterson and Cory (1966) and Williams *et al.* (1967). The procedure involved the extraction of the soil with 1N NH₄Cl, 0.5N NH₄F, 0.1N NaOH, 0.5N H₂SO₄, 0.3N sodium citrate (with solid sodium dithionite), and finally with 0.1N NaOH for the extraction of Fe Al-phosphate, Ca-phosphate, and reductant soluble phosphate respectively.

Extraction of Al and Fe Phosphate

Soil sample (0.5 g, oven-dry basis) was put into a 50 ml centrifuge tube. Iron and aluminum phosphates were extracted by adding 25 ml of 0.1M NaOH and 1M NaCl solution to centrifuge tubes. The tubes were sealed with stoppers, shaken by hand, and then placed on a mechanical shaker for 17 hours. The samples were centrifuged at 2000 rpm for 15 minutes. After centrifugation, the supernatant was transferred into a 50 ml volumetric flask. The soil was washed twice with 12.5 ml of saturated NaCl and centrifuged again. The washings were combined with the extract and brought to volume, after which the phosphorus in the extract solution was analyzed.

Extraction of Reductant Soluble Phosphate

20 ml of 0.3 M sodium citrate and 2.5 ml of 1 M NaHCO₃ were added to the soil residues left after extracting iron-phosphate. The suspension was heated in a water bath at 85°C, and then

1.0 g of sodium dithionite was introduced. The suspension was stirred vigorously to extract the reductant-soluble phosphorus and heated for an additional 15 minutes. It was then centrifuged at approximately 2000 rpm for 15 minutes, and the supernatant was transferred to a 50 ml volumetric flask. The soil was washed twice with 12.5 ml of saturated NaCl, and the washings were centrifuged. These washings were combined with the extract and brought to volume. The extract was exposed to air to oxidize the sodium dithionite, and the supernatant solution was then preserved for analysis.

Extraction of Calcium Phosphate

To the residues in the centrifuge tube, 25 ml of 0.5 M HCl was added, and the tubes were sealed and shaken for 1 hour. The suspension was then centrifuged at 2000 rpm for 10 minutes. The supernatant was decanted into a 50 ml volumetric flask. The soil was washed twice with 12.5 ml of saturated NaCl each time and centrifuged again. The washings were combined with the extract and diluted to the final volume. The supernatant solution was collected for phosphorus determination.

Method of Phosphorus determination from the extracts

Inorganic phosphorus was measured by the ascorbic acid blue color method of Murphy and Riley (1962). 4 ml of 0.8 M H_3BO_3 was added to ammonium fluoride extract just before color development. Reductant soluble phosphate was determined after oxidation of dithionite by allowing the flask to stand exposed to the atmosphere (Williams *et al.*, 1967) before color development. The difficulty, however, arose during the determination of phosphorus from the extract. To oxidize the dithionite, the samples needed to be heated with H_2O_2 .

Results and Discussion

The inorganic P including iron aluminium P, calcium bound P, and residual P is the major contributor to total P in soil. The number of different forms of inorganic P in soil depends on the nature of soil quality. Inorganic P exists in various forms, including labile and moderately labile P, which are influenced by soil management practices and environmental conditions (He *et al.*, 2013) (Tiecheret *et al.*, 2012).

Inorganic Phosphorus Fractions in Soil

The modified fractionation scheme of soil inorganic phosphorus of Chang and Jackson (1957) as reported by Kuo (1996) was used to quantify the fractions of soil P as affected by different salinity levels.

Fe and Al Bound Phosphate

The Fe Al-P contents of the soils at different time intervals as affected by the application of different salinity levels are presented in Fig1 and Fig 2. In Bajoa series the Fe-Al-P content decreases with increasing salinity levels and remains constant from 30th to 60th day. The percent (81.6%) decrease of Fe-Al-P content in the salinity level of 12 dSm⁻¹ is higher than the percent (87.5%) decrease of 2 dSm⁻¹. In Sara series, the Fe Al-P content remains nearly constant. there is no significant effect of salinity levels on Fe-Al-P contents.

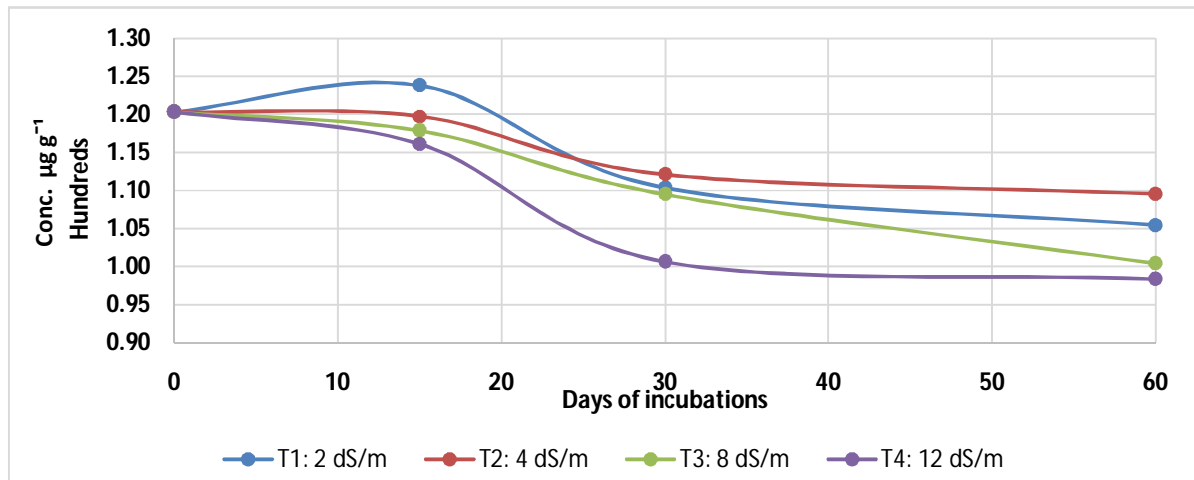


Fig. 1 Changes in Fe Al-P content in Bajoa series under different salinity treatments

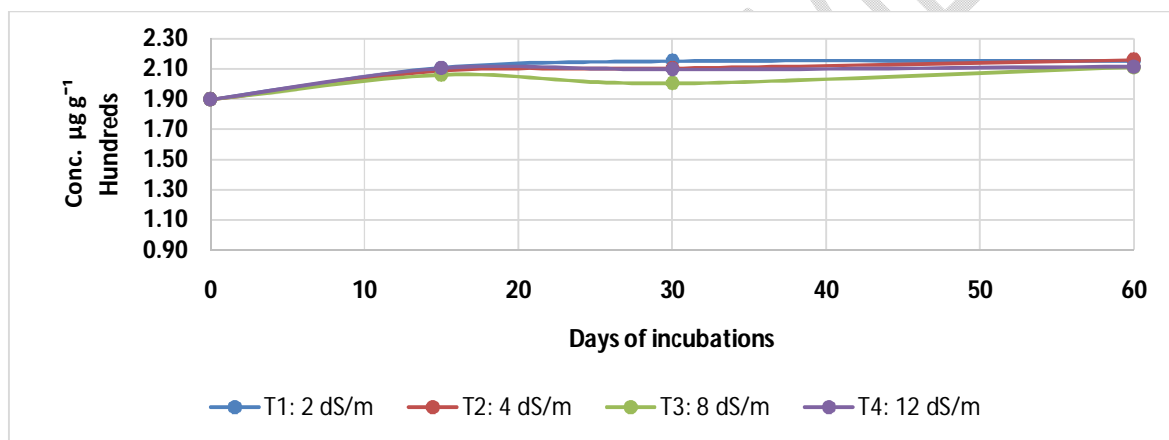


Fig. 2 Changes in Fe Al-P content in Sara series under different salinity treatments

Reductant Soluble Phosphate

The Rs-P contents of the soils at different time intervals as affected by the application of different salinity levels are presented in Fig. 3 and Fig. 4. In the Bajoa series with the increasing salinity level the Rs-P content decreases. Though at the salinity level of 2 dSm^{-1} the Rs-P content increases but this cannot stay long with increasing salinity level. In Sara series, it also shows the same result as the Bajoa series. With the increasing salinity level, it shows a periodic decrease of Rs-P content.

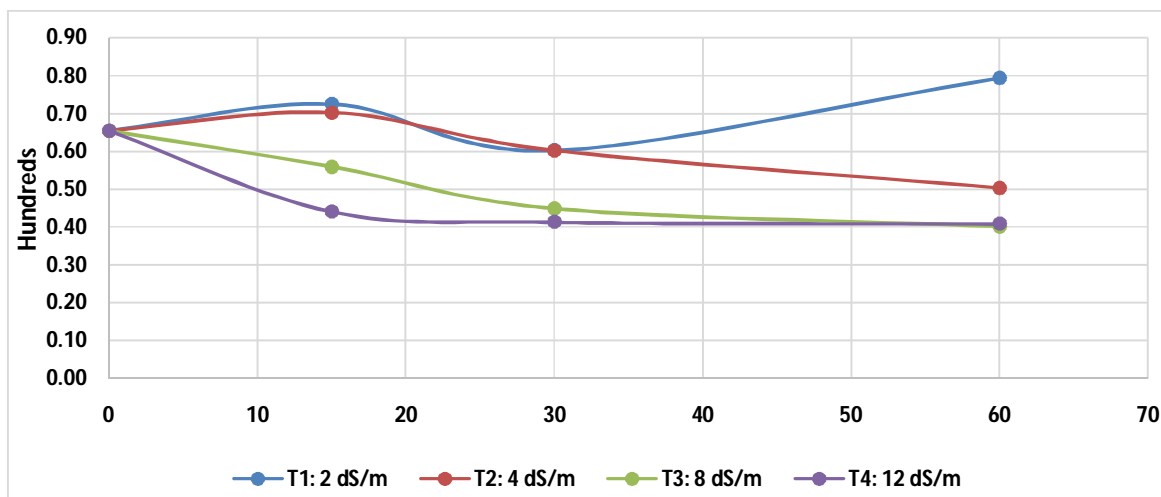


Fig. 3 Changes in RS-P content of Bajoa series under different salinity treatments

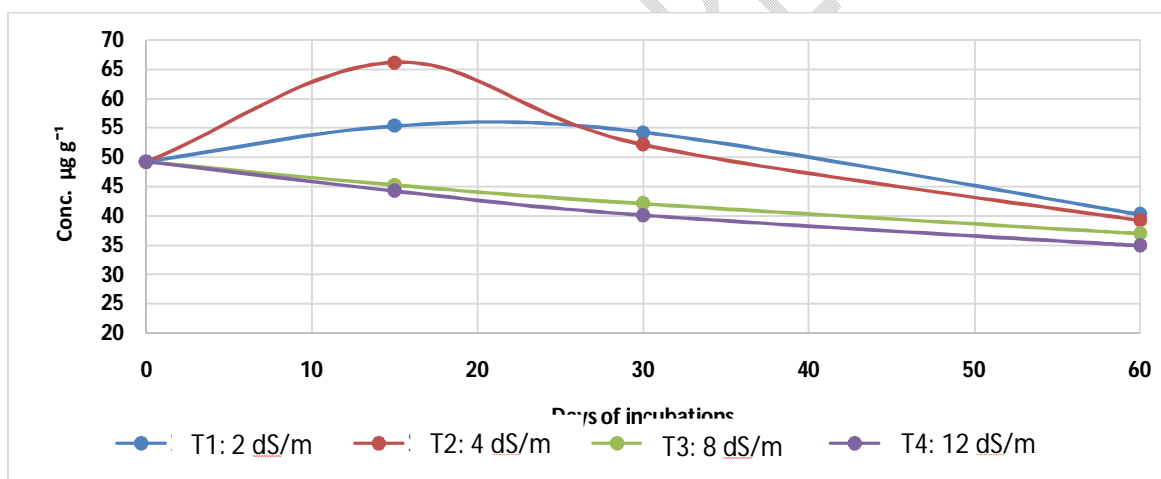


Fig. 4 Changes in RS-P content in Sara series under different salinity treatments

Calcium Phosphate

The Ca-P contents of the soils at different time intervals as affected by the application of different salinity levels are presented in Fig 5 and Fig 6. In the Bajoa soil series against two salinity levels (2dSm^{-1} and 4dS m^{-1}), the Ca-P percentage (110.37 and 112.17) % tends to increase. But with the increasing salinity level of 8dSm^{-1} and 12dSm^{-1} , the Ca-P percentage

(95.39 and 90.24) % decreases. In Sara soil series with the increasing salinity level, the Ca-P percentage (from 109.18 to 135.23) % increases.

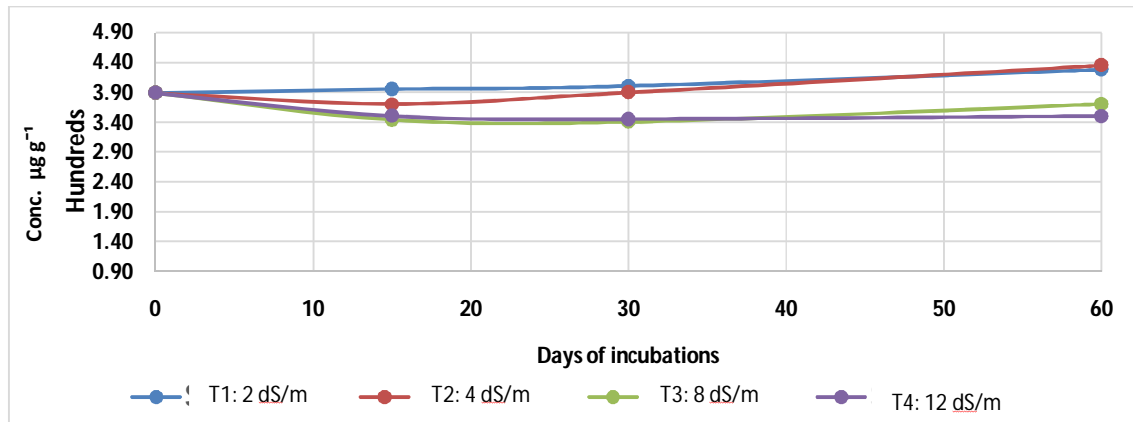


Fig. 5 Changes in Ca-P content in Bajoa series under different salinity treatments

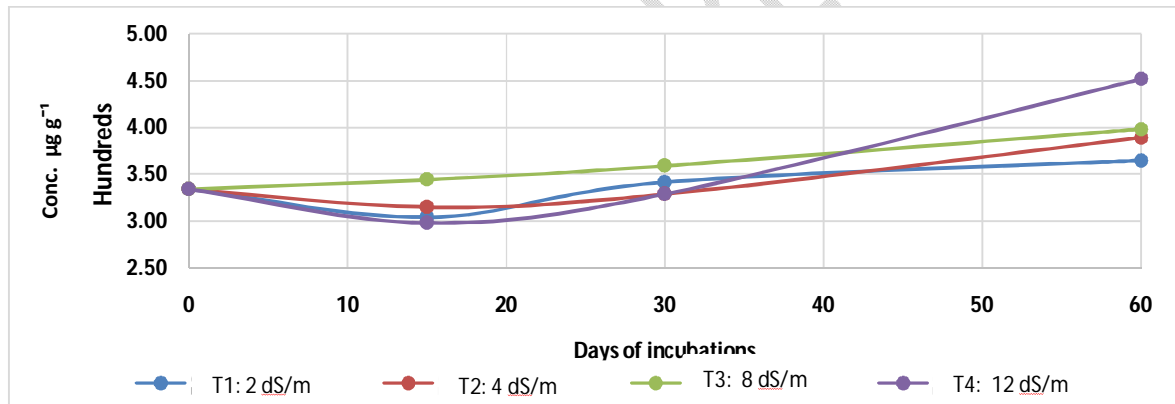


Fig. 6 Changes in Ca-P content in Sara series under different salinity treatments

Conclusion

This study evaluated the effects of four salinity levels (2 dS m^{-1} , 4 dS m^{-1} , 8 dS m^{-1} , and 12 dS m^{-1}) on phosphorus (P) transformation and availability within the Bajoa and Sara soil series over four incubation periods (0, 15, 30, and 60 days). Results indicate that increasing salinity significantly alters the distribution of inorganic P fractions, affecting their availability for plant uptake. The changes in the P fractions follow the following sequences:

Ca-P>Fe, Al-P> Rs-P in Sara series (pH 7.56)

Ca-P>Fe, Al-P> RS-P in Bajoa series (pH 6.97)

Phosphorus fractions were observed to follow distinct transformation sequences in both soil series, with calcium-bound phosphorus (Ca-P) predominating over iron and aluminum-bound phosphorus (Fe, Al-P) and reductant-soluble phosphorus (Rs-P). Salinity increased the fixation of phosphorus in less bioavailable forms, thus reducing the overall availability of P to plants. Both the Sara and Bajoa soils exhibited similar behaviour, showing a decrease in P availability as salinity levels rose. These findings underscore the detrimental impact of salinity on phosphorus bioavailability, with potentially significant implications for crop productivity in salt-affected regions. The rapid transformation of phosphorus fractions under saline conditions highlights the need for targeted phosphorus management strategies that consider soil salinity. Future research should explore long-term field studies and advanced phosphorus management techniques to improve nutrient availability and crop resilience in saline soils.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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