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Determining critical soil pH for phosphorus uptake efficiency in an acidic Ultisol for maize

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THE scarcity of phosphorus (P) restricts crop growth due to reduced P uptake in acidic soil. Due to significant variations in soil pH in acidic Ultisol, it is still unclear how such variations would affect P uptake efficiency by maize plants. Thus, under different pH (3.75, 4.0, 4.5, 5.0 and 5.5) conditions, this study investigated the growth and P uptake efficiency during the growth of maize plants as influenced by the distribution of P species in Ultisols. Our results showed that increased soil acidity had a negative impact on plant height, dry matter yield (shoots and roots biomass), and chlorophyll content of maize plants. Also, the P uptake efficiency increased with decreased soil acidity, and the critical value for P uptake efficiency was pH 5.00. Generally, as soil pH was increased, soil available P decreased significantly and was consistent with higher uptake of available P by the plant and variations in different P species including those bound to iron, aluminium, and calcium.

Keywords: Acidification, Phosphorus speciation, Chlorophyll, Plant biomass, Nutrient availability.

1. Introduction

Phosphorus (P), an essential macronutrient, is vital for plant growth and development (Gilbert 2009, Farrag and Bakr 2023). However, P shortages limit agricultural output, prompting the use of P fertilizers to improve crop yield (Hurisso et al. 2021; Grant and Flaten 2019). However, the fixation of soluble P to soil is prominent, especially in acid soils, thus, limiting its availability for plant utilization (Baquy et al. 2022). It is estimated that more than 90 kg P ha^{-1} year^{-1} of the applied P fertilizer is fixed into the soil which results in low P use efficiency (Zhang et al. 2019). Soil pH being a major influencing factor of soil physicochemical properties, it has a major role in controlling P availability and P use efficiency. Thus, increasing P use efficiency during P fertilizer application by manipulating soil pH can be an important strategy needed for sustainable crop production.

One of the primary causes of decreased P use efficiency in crop plants is soil acidity (Omenda et al. 2021, Khalil et al. 2023). Acid soils are predicted to cover around 3.95 billion hectares of global land area (Von Uexküll and Mutert 1995) and Ultisols cover ≈8% of the ice-free landmasses in the world. Given that these soils are easily acidified and characterized by large amounts of iron (Fe)/aluminum (Al) oxides, they are prone to P shortages due

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to immobilization (Fageria 2016; Nkoh et al., 2022). In acid soil, 70-90% P of applied fertilizer is fixed and unable to fulfill immediate plant P requirements (Fageria 2016). It is well documented that hydrous oxides of Fe and Al, crystalline or amorphous Al, silicate, and calcium (Ca) carbonate are the principal soil minerals that fix P (Sample et al. 2015, Baquy et al. 2020). The need to increase P availability has led to the over-application of P fertilizers, which has been observed to worsen the P fixation problem (Sayed et al. 2024).

The liming effect on P release can increase P availability in acidic soils. This effect of lime is also known as the “P spring effect” (Bolan et al. 2003). It is reported that when soil pH increased from 4.19 to 5.35 due to the application of lime, soil availability P was also significantly increased (Haling et al. 2010). In variable-charged soils, the P spring effect is described as a reduction in pH with increased anion exchange capacity, which enhances P retention. Bolan et al. (2003) showed that exchangeable and soluble Al might liberate plant-available P by reducing the Al content due to the application of lime in the soil. The release of P ions from Al and Fe oxides is associated with the increase of soil pH from 5.0 to 6.5 (Szogi et al. 2024). But, the effects of liming on P spring in extremely weathered acidic soils have brought contradictory results (Ping et al. 2020; Wang et al. 2024). However, in acidic soil, Al-P and Fe-P species showed a positive and significant correlation with plant-available P and plant P uptake (Bhardwaj et al. 2005, Farid et al. 2023).

Soil acidification due to various anthropogenic causes lowers soil pH (Meng et al. 2019; Raza et al. 2020). To neutralize the soil, a greater amount of liming materials is required for improved yield potential. Over-liming may also create problems as soil pH is related to different soil properties, especially soil P availability. Thus, the critical soil pH must be determined for acid soil amelioration and associated mechanisms to increase applied P use efficiency (Baquy et al. 2017; Hong et al. 2018). The critical or threshold soil pH is an important parameter for calculating the exact amount of lime to achieve the required soil pH level. The known threshold pH value assists in reducing soil acidity, while also increasing P use efficiency (Baquy et al. 2018 Pan et al. 2020). Because P use efficiency is substantially reduced below critical soil pH, the value of critical soil pH is crucial to increase the P use efficiency. Generally, when soil pH decreases below a threshold, the effect of acidity on P use efficiency becomes significant. Nevertheless, the experimental evidence to support this hypothesis remains limited.

In acid soil, a higher rate of fertilizer application and other anthropogenic effects decrease the soil pH, leading to a greater P fixation by Al and Fe, and inorganic P is directly connected to the transformation and formation of available P (Wang and Zhang 2010). P fertilizer application may increase the content of available P in soil (Reimer et al. 2020, El Nakma et al. 2024), however, how added P in the soil is impacted by different soil pH levels remains elusive. We hypothesized that the P uptake efficiency by crop plants will be influenced by different soil pH levels and different P species. The P use efficiency must be improved by lowering P fertilizer inputs and decreasing P fertilizer losses due to fixation (Zhang et al. 2019). As P availability is directly linked to soil pH, it is essential to evaluate soil critical pH for optimum P use efficiency and the associated role of different P pools on P uptake. Therefore, the main objective of this study was to investigate the critical soil pH for phosphorus use efficiency for maize growth in acidic soil.

2. Materials and Methods

2.1 Soil sampling and incubation experiment

The Ultisol was collected from Langxi ($31^0$6' N, $119^0$8' E), Anhui province, China, and the land-use system was mustard during soil collection. The soil originating from quaternary red earth was sampled from the top layer (0-15 cm), air-dried, and ground to pass through a sieve of 2.0 mm. The soil pH in water (3.97), organic matter content (18.17 g kg^{-1}), cation exchange capacity (12.50 $cmol_c$ kg^{-1}), available P (347.84 mg kg^{-1}), and exchangeable aluminum (5.24 $cmol_c$ kg^{-1}) have been determined and reported elsewhere (Baquy et al. 2018b). The initial soil had a high concentration of available P because a large amount of nitrogen-phosphorus-potassium (NPK) fertilizer was applied to increase the growth of mustard crops during that season.

A soil incubation experiment was conducted before pot culture to adjust soil pH values using $Ca(OH)_2$ and $Al_2(SO_4)_3$ following previous experiments based on a soil-lime experiment (Baquy et al. 2018b). We considered both $Ca(OH)_2$ and $Al_2(SO_4)_3$ for increasing or decreasing the soil pH from the initial soil pH, respectively. Briefly, a 100 g portion of air-dried soil sieved through a 2 mm sieve was weighed into plastic cups and mixed with incremental levels of $Ca(OH)_2$ or $Al_2(SO_4)_3$ (0.1, 0.2, 0.3, 0.4, and 0.5 g). Distilled water was used to moisten the soil to 70% of field capacity and then the cups were covered with perforated plastic films to encourage aeration and incubated in the dark at 25 °C for 15 d (Percival 136NL incubator; Percival Scientific, Perry, IA, USA). The water content was replenished every three days with distilled water and at the end of incubation, the soil pH was measured. The relationship between soil pH and the amendments was established to obtain a standard curve.

2.2 Pot culture experiment

A pot culture experiment was executed in a glass greenhouse environment. A soil pH gradient was considered for this experiment and distributed as 3.75, 4.00, 4.50, 5.00, and 5.50. Each treatment was repeated three times. The experiment was set up in a completely randomized design with each pot containing 750 g of $Ca(OH)_2$ or $Al_2(SO_4)_3$-treated soil; to increase or decrease the soil pH from the initial to the target pH. After mixing the amendments, soils were then incubated at 25 °C for 15 d as mentioned above. After pre-incubation, a basal dose of urea and monopotassium phosphate was added to each pot at the rate of 250 mg N and 35 mg P kg^{-1} soil, respectively.

A maize variety mildly sensitive to soil acidity, Zhendang 958, was selected for growing. Before sowing, seeds were surface-sterilized for 15 minutes with 10% H_2O_2, cleaned with running tap water, and distilled water, and then let to germinate in a biochemistry chamber without light at 25 °C. After three days of germination, the seeds were then transferred to the pot. Each pot contained eight germinated seeds, and after the emergence, plants were reduced to 5 in each pot. The crops were grown in a climate-controlled Percival 136NL incubator. Each pot received the necessary amount of distilled water to maintain it to 70% of field capacity. The day and night temperatures were 28 and 23 °C while the relative humidity was 70 and 60%, respectively. The day length was 14 h and the light intensity was 400 µmol photon $m^{-2}s^{-2}$.

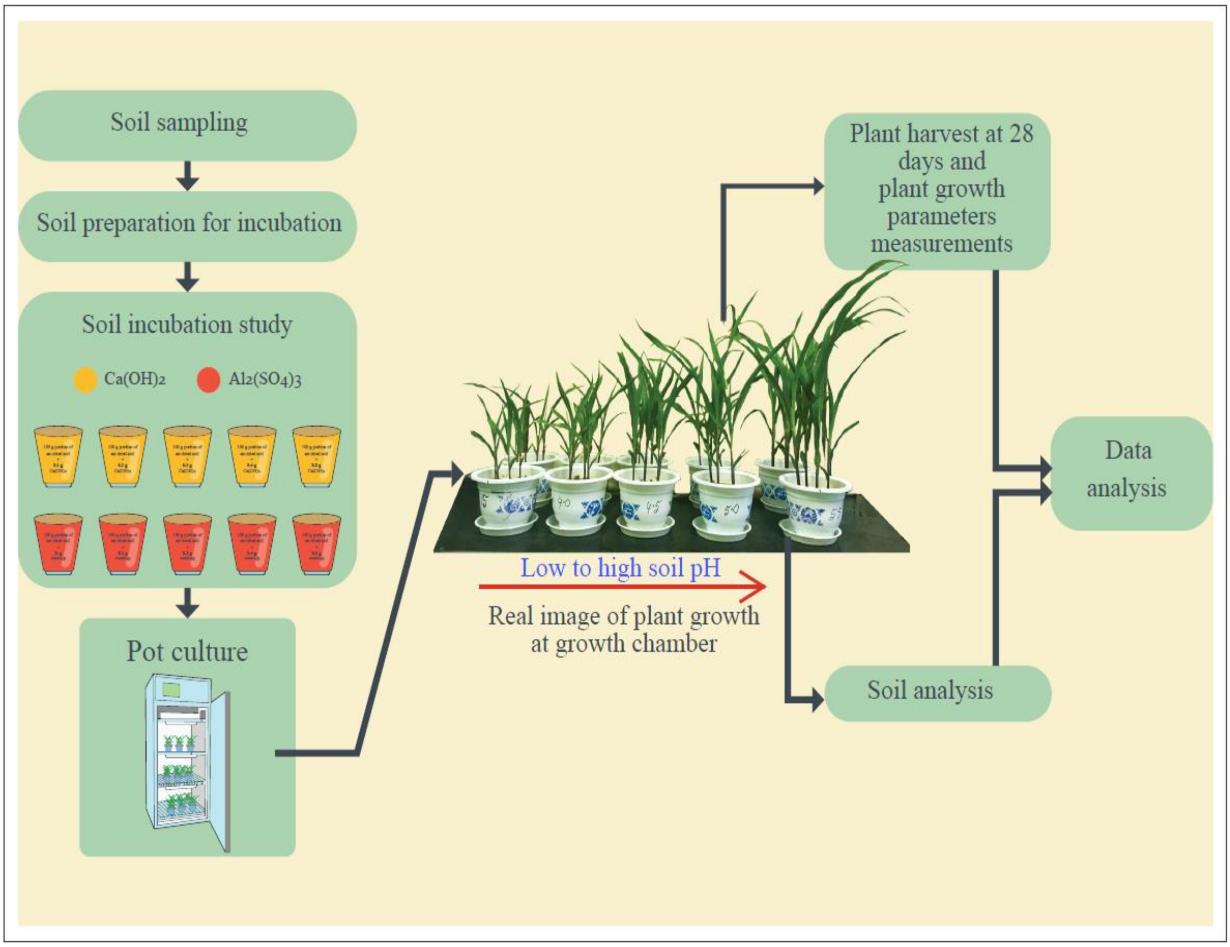

Fig. 1. Flowchart of incubation and pot culture study.

After 28 d of growth, all the plants were harvested. In this study, the plants were harvested during the vegetative stage, even though the typical growth cycle of maize is approximately 200 days. Given the limited space in our controlled growth chamber, we focused solely on the vegetative stage of plant growth. Before harvesting, SPAD values were measured at the third leaf stage in each plant with a SPAD-502 plus chlorophyll meter (Konica Minolta Sensing, Tokyo, Japan). The plant's height was measured with a ruler that had a ±0.1 cm deviation. Shoot and roots were harvested separately and washed with distilled water. The plant materials were dried at 105 ℃ for 2 h and then at 70 ℃ to constant weight.

One part of the plant sample was used to measure P uptake and the uptake efficiency of P was calculated as the total P uptake by plants (g pot^{-1}) to the applied P (g pot^{-1}) and expressed by percentage (White. 2009). Soils were collected from each pot after crop harvest, air-dried, and ground to pass through a 0.3 mm sieve. In a 1:2.5 ratio of soil:water suspension, the pH of the soil was determined with an Orion A211 pH meter. The mean soil pH data were used in this manuscript as 4.0, 4.5, 4.72, 5.07, and 6.02.

The inorganic phosphorus species were measured following the sequential extraction method (Kuo, 1996). Soluble or loosely bound P, aluminium-bound P (Al-P), iron-bound P (Fe-P), occluded P, and calcium-bound P (Ca-P) were extracted with 1.0 M NH_4Cl, 0.5 M NH_4F at pH 8.2, 0.1 M NaOH, 0.3 M $Na_3C_3H_6O_7$, and 0.25 M H_2SO_4, respectively. After each stage, the soil was washed with saturated NaCl and centrifuged twice and the supernatant after centrifugation was combined with the previous filtrate. The phosphorus standard curve was established to measure phosphorus concentration following previous literature (Murphy and Riley 1962).

2.3 Statistical analyses

The experimental data were evaluated by one-way ANOVA using SPSS 20.0 (SPSS Inc., Chicago, IL, USA) and Duncan's multiple range test used to estimate the significant differences between P fractions and soil pH at 5%. Also, the Person correlation coefficients were determined for soil inorganic P-fractions, soil pH, and P uptake efficiency of maize. Additionally, soil critical pH was obtained by fitting the data with a piecewise two-segment linear function of Origin Pro 2018 software.

3 Results

3.1 The relationship between soil pH and maize growth

The effect of soil pH (4.00-6.02) on maize growth was evaluated by considering different plant growth parameters including plant height (Fig. 2A), chlorophyll content (Fig. 2B), root (Fig. 2C), and shoot dry weight (Fig. 2D). The results show that soil acidity has a negative impact on maize plant height and the plant height significantly increased with an increase in soil pH (Fig. 2A). Our study revealed that the critical soil pH for maize plant height was pH 5.36 with the correlation of $r^2 = 0.91$. Below this critical pH, plant height was reduced by soil acidity. Following the negative impact of acidity on plant growth, the chlorophyll content (SPAD value) of maize leaf was equally affected (Fig. 2B). For chlorophyll content, the critical soil pH was found at pH 5.0 with a correlation coefficient of $r^2 = 0.62$. This indicates that above the critical pH value, there was less influence of soil acidity on chlorophyll content and this agrees with the non-significant difference among treatments at pH > 5.0. However, below this pH value, the chlorophyll content was significantly decreased, with the most negative effect observed at pH 4.0. The shoot dry weight showed a decreasing trend as the soil pH was decreased (Fig. 2D) and the critical soil pH for optimum shoot growth was 4.99. However, the correlation between soil pH and the shoot dry weight was significantly low with a correlation coefficient of $r^2 = 0.34$, indicating that the effect of soil acidity on the shoot dry weight was indirect.

3.2 Effect of soil pH on the forms of inorganic phosphorus

Soil pH and P species showed differential relationships along a pH gradient (Fig. 3). Soil soluble P increased to a maximum (68.11 mg kg^{-1}) at pH 4.50 before significantly decreasing thereafter to a minimum (22.64 mg kg^{-1}) at pH 6.02 (Fig. 3A). For aluminum-bound P (Al-P), there was no statistically significant difference between the treatments. Nevertheless, Al-P decreased with increasing soil pH from 174.67 mg kg^{-1} at pH 4.00 to 159.91 mg kg^{-1} at pH 6.02, with the lowest value registered at pH 5.52 (152.62 mg kg^{-1}, Fig. 3B). Iron-bound P (Fe-P) showed an increasing trend from the lowest of 319.27 mg kg^{-1} at pH 4.00 to a maximum of 362.04 mg kg^{-1} at pH 4.72 and then decreasing to 357.80 mg kg^{-1} at pH 6.02 (Fig. 3C). Soil occluded P showed no significant differences under different pH conditions (Fig. 3D), with the lowest occurring at pH 4.00 (23.60 mg kg^{-1}) and the largest at pH 4.72 (32.27 mg kg^{-1}). Unlike occluded P, Ca-P showed a continuously increased trend with pH (Fig. 3E). For example, at a low pH of 4.00, Ca-P was 30.35 mg kg^{-1}, which was increased by 46.98% and 61.59% at pH 5.07 and 6.02, respectively.

Soil P uptake efficiency by maize plant showed significant variations with changes in soil pH (Fig. 4) and consistent with variations in the different P forms under different pH conditions (Fig. 3). At lower soil pH (4.00) just about 8.32% of available P was taken up by the plant and this efficiency was increased between 12.90% to 56.37% as the pH increased from 4.50 to 6.02. Our results revealed that the critical soil pH for P uptake efficiency was at pH 5.0 with the correlation coefficient of $r^2 = 0.83$. Below the soil pH 5.0, the P use efficiency was affected by soil acidity while above the critical soil pH, P uptake efficiency was increased with increasing soil pH and reducing soil acidity. The Pearson correlation analysis revealed a significant ($P < 0.05$) negative relationship between soil pH and soluble P (Table 1). Also, there was a significant positive relationship between soil pH and Ca-P ($P < 0.01$) and P uptake ($P < 0.01$) efficiency while the relationship between soluble P and P uptake efficiency was significantly negative. Although insignificant, there existed a negative relationship between Al-P and Fe-P, occluded-P, Ca-P, and P uptake efficiency. Also, the relationship between Ca-P and P uptake efficiency was significant at $P < 0.01$.

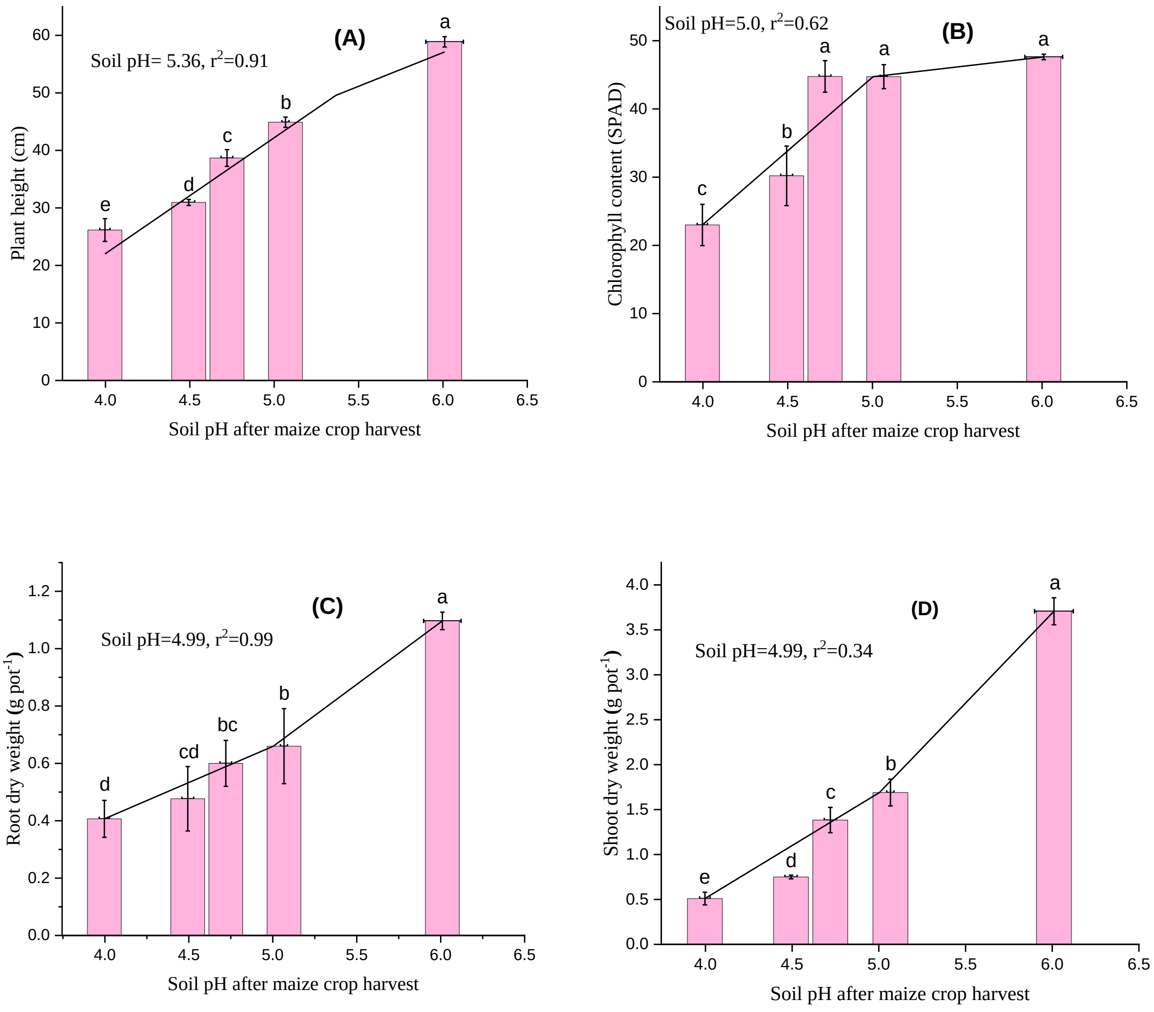

Fig. 2. Maize plant height (A), chlorophyll content (SPAD value, B), maize shoot (C), and root dry matter yield (D) as a function of soil pH. Different letters on pillars indicate significant differences among treatments (*P* < 0.05).

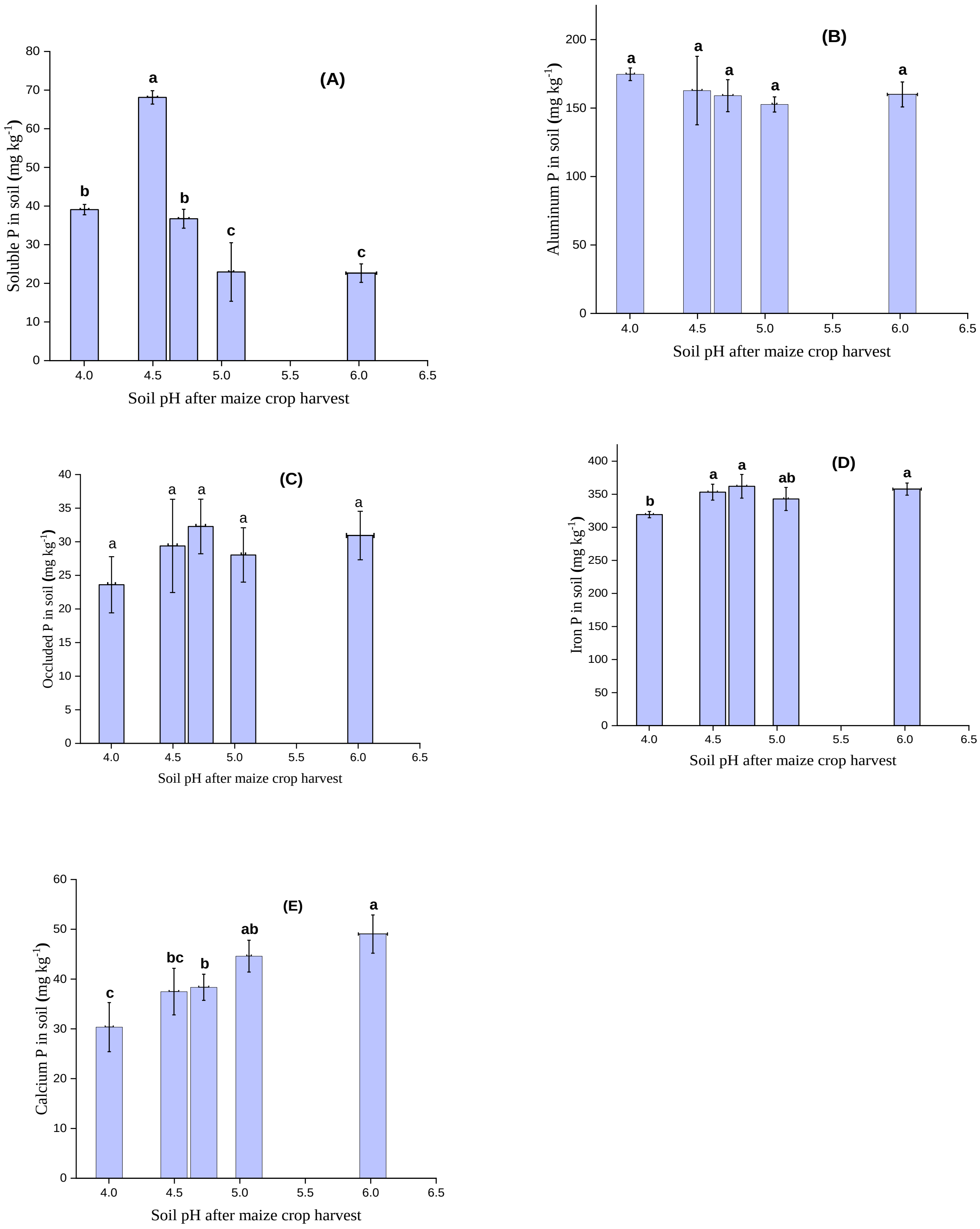

Fig. 3. Soluble (A), aluminum-bound (B), iron-bound (C), occluded (D), and calcium-bound (E) phosphorus after maize crop harvest as a function of soil pH. Different letters on pillars indicate significant differences among treatments ($P < 0.05$).

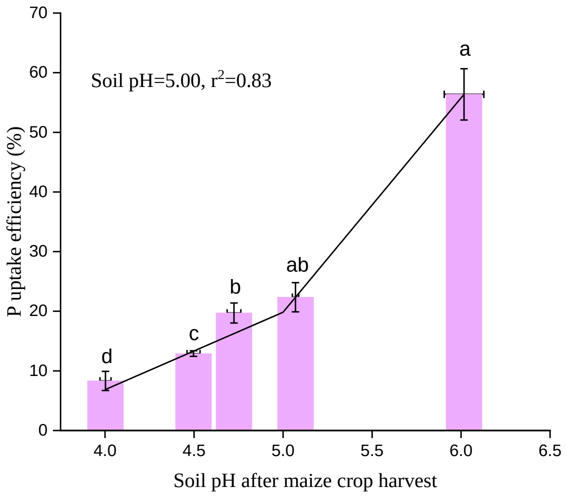

Fig. 4. Phosphorus uptake efficiency by maize crop as a function of soil pH. Different letters on pillars indicate significant differences among treatments (*P* < 0.05).

Table 1 Correlation coefficients (Pearson correlation) between soil inorganic P-fractions and P uptake efficiency by maize (n = 15)

Parameters	pH	Soluble P	Aluminum P	Iron P	Occluded P	Calcium P	P uptake efficiency
pH	1	-0.573*	-0.372	0.493	0.375	0. 863**	0.985**
Soluble P		1	0.175	-0.049	0.014	-0.440	-0.659**
Aluminum P			1	-0.400	-0.192	-0.330	-0.307
Iron P				1	0.478	0.382	0.473
Occluded P					1	0.591*	0.376
Calcium P						1	0.855**
P uptake efficiency							1

*Correlation is significant at the 0.05 level (2-tailed) and **Correlation is significant at the 0.01 level (2-tailed).

4. Discussion

Generally, the negative impact of soil acidity on crop growth is related to the inhibitory effect of Al^{3+} on root elongation (Shi et al., 2020). Since the shoot has no direct contact with Al^{3+}, it can be inferred that the observed effect of soil acidity on shoot dry weight was due to its effect on root growth. Following this reasoning, our result shows that the root dry weight increased with increasing soil pH, particularly above the critical soil pH of 4.99 (Fig. 2C). From the correlation coefficient ($r^2 = 0.99$), it can be deduced that soil acidity has a direct effect on root growth. As the soil pH was increased to pH values > 4.99, soil exchangeable acidity became minimal and the toxic Al^{3+} was hydrolyzed, hence, reducing toxicity on root and general plant growth.

All the plant growth parameters were negatively affected by increasing soil acidity as the soil pH was decreased from pH 6.0 to 4.0. At lower soil pH, plant height was lower than that of higher soil pH and this was due to higher Al^{3+} concentration (Jones et al. 2019). Excess Al^{3+} in the soil solution can interfere with the utilization, transport, and uptake of essential plant nutrients such as P, Ca, and Mg, water uptake potential, and enzymatic activity in the roots (Barcelo and Poschenrieder 2002; Jiang et al. 2015). The overall effect of these above reasons was reduced plant growth, which has been observed and documented in terms of inhibited root elongation and decreased plant height and total dry matter (Watanabe et al. 2006; Joris et al. 2013; Baquy et al., 2017; de Vargas et al. 2019; Shi et al., 2020). Our study shows that even though plant growth was inhibited and showed significant variations with pH, the plant photosynthetic efficiency (reflected by the content of chlorophyll) was only significantly affected at pH values ≤ 4.5 (Fig. 2B). This is probably because at pH values < 5.0, the concentration of Al^{3+} in soil solution is high and studies have shown that the presence of Al^{3+} affects the chlorophyll concentration of plant leaves (Rance et al. 2020; Zhang et al., 2007).

Soil pH greatly influences soil physicochemical properties and controls the basic properties of the different forms of inorganic P (Sharpley 2000). Specifically, soil pH controls the forms and solubility of different phosphate compounds including those bound to Al, Fe, and Ca (Penn and Camberato 2019) and this is consistent with the results shown in Fig. 3. Inorganic P fertilizers applied to agricultural soils are fixed to soil minerals differently under different soil pH and organic matter levels (Nkoh et al., 2022). Soil biological processes influence P solubility by transforming different P species to soluble P. Soil microbes and phosphate enzymes help in the transformation and solubilization of inorganic fixed P in soil and make the P available to plants (Wang and Zhang 2008; Alam et al. 2023; Ping et al. 2024). The magnitude of this transformation varies significantly with pH given that soil properties differ under different soil pH conditions and is consistent with the significant positive relationship between soil pH and soluble P and Ca-P in this study (Table 1). Although the changes in Fe-P and Al-P did not show significant variations with pH, the changes observed indicate that soil pH was an important determinant influencing the transformation, solubilization, and utilization of inorganic P by plants. Pierzynski et al. (2018) found that P availability was increased because Fe-adsorbed P species were common in P fertilizer-treated soils. However, the present study found that there was no influence of Fe-P on P availability as the increasing or decreasing trend was not consistent in terms of different soil pH levels. This might be due to the effect of added aluminum in soil.

It is important to note that the low availability of Fe-P and Al-P is due to lower changes in these P species with changing pH conditions. In addition to the direct effect of soil pH on different inorganic P species, soil pH also affects P availability indirectly by its impact on the soil properties. In this study, a positive significant relationship existed between soil pH and P uptake efficiency by maize plants. This might be due to decreased adsorption of phosphate with increased soil pH (Jiang et al. 2015; Baquy et al. 2020; Nkoh et al., 2022). The overall results from this study indicate that P species and availability of applied P-containing fertilizers depend on soil pH. Nevertheless, soil pH ranging from 6.5-7.0 is favorable for maximum P uptake by crops, even though maximum pH uptake by plants can occur at pH values lower than 6.5 (Penn and Camberato 2019). Our findings revealed that soil acidity had an insignificant influence on P uptake efficiency above the critical soil pH (5.00, Fig. 4), and is consistent with the critical soil pH for different plant growth parameters (Fig. 2). The optimum pH level for obtaining the best available P in soil is typically between 5.5 and 6.5. Our study focused only on the critical value, which is the threshold at which plants begin to exhibit deficient symptoms, rather than the optimal level of P. Thus, it is recommended that the soil pH should be kept at or above pH 5.00 to avoid decreased P use efficiency in acidic soils.

Acidic Ultisols are inherently deficient in soil fertility, particularly in terms of P (Dejene et al. 2023; Hua et al. 2023). Intensive and excessive inorganic P fertilizers are applied to the soils to attain maximum crop production, leading to higher P accumulation and lower P utilization by crop plants. The enhancement of P uptake efficiency in crop plants to achieve an optimum yield is essential due to the importance of P in agriculture and its limited availability in most soils. Plants can uptake P from the soil as inorganic orthophosphate. ($H_2PO_4^-$, HPO_4^{2-}, or PO_4^{3-}). However, $H_2PO_4^-$ is the main form of P in acidic soils while in neutral soils, HPO_4^{2-} is the principal form of P, and PO_4^{3-} is the major form of P in alkaline soils (Ducousso-Détrez et al. 2022, Bing et al. 2023). The solubility of different P species depends on various soil chemical properties like pH. In acidic conditions of the soil, the presence of Al and Fe is high. The higher presence of Al and Fe promotes the precipitation of soil P as insoluble Al or Fe phosphates. At higher soil pH, P fixation is associated with Ca ions. When soil pH is more than 6.5, P is fixed with Ca as insoluble Ca phosphate. Thus, the fractionation study of P is a practical way to study the impact of soil properties on the availability of P for plant uptake as well as the transformation of different P species (Wang et al. 2023; Biassoi et al. 2023).

5. Conclusions

In this study, we evaluated the effect of soil acidity on plant growth parameters by evaluating its effect on P-use efficiency during maize growth. Interestingly, increased soil acidity significantly influenced all plant growth parameters evaluated in this study, with parameters such as plant height, chlorophyll content, dry weight of maize shoot and root increasing with decreased soil acidity. Overall, the plant growth parameters were enhanced at a pH of 5.0 and subsequently at different pH levels. This observation is consistent with the change in maize P uptake efficiency under different pH conditions. In the acidic Ultisol used in this study, we observed that the critical soil pH for P uptake efficiency by maize crop was 5.00. The improved P uptake by the maize plant was due to the conversion of different P species into soluble P under changing soil pH, and plant growth was reliant on the nature of different P species. Nevertheless, further research is needed to ascertain whether the critical soil pH values observed in this study for maize growth and P use efficiency could apply to other soil types and crop varieties.

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Data availability statement

All data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Not applicable

Conflict of interest

There are no real or perceived financial conflicts of interest for the authors.

Authors' contributions

M.A.A. Baquy: Conceptualization; Methodology; Investigation; Data curation; Formal analysis; Writing-original draft. Jiu-yu Li, M.R. Biswash and J.N. Nkoh**:** Conceptualization; Formal analysis; Project administration, Supervision; Writing-review & editing; Ren-kou Xu**:** Conceptualization; Writing-review & editing; Funding acquisition.

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