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DIFFERENTIAL BENEFITS OF ROCK PHOSPHATE (RP) BY TOMATO (*LYCOPERSICON ESCULENTUM* MILL.) PLANT AS AFFECTED BY NITROGEN FORMS AND SOIL TYPES

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ABSTRACT

Phosphorus is one of the critical elements that limit plant production, particularly in humid and semi-humid soils. For realization of African Green Revolution, use of rock phosphate (RP) by resource-poor farmers may be an alternative to more expensive water soluble phosphate (P). Utilization of RP was investigated in tomato (*Lycopersicon esculentum Mill*) var; Moneymaker in minirhizotrons at Hohenheim to assess root-induced chemical changes in the rhizosphere with two soil types: - Arenosol and C-horizon of Luvisol. Additionally, field experiments were conducted at Kibwezi and Maseno (Luvisol and Ferralsol, respectively) in Kenya. All trials received RP and soluble P as source of P and nitrate and ammonium (stabilized with DMPP as nitrification inhibitor) as nitrogen sources. Ammonium treatment significantly reduced rhizosphere pH in minirhizotron treatment with Arenosol with corresponding increase in shoot P content (but with significant negative shoot biomass accumulation), while rhizoplane pH differed significantly from rhizosphere pH treatment with C-horizon of Luvisol and there was no RP benefit to plant. The buffer capacity of the Luvisol was quite high and the pH 2mm away from rhizoplane was similar to that of bulk soil. However, minimal NO_3^- additions to ammonium treatment significantly improved biomass production in both soils. In both rhizobox experiments, NO_3^- led to rhizosphere alkalinization. Both shoot and fruit biomass was enhanced by RP application at Maseno, while RP had a negative effect on tomato plant production at Kibwezi. Therefore, role of RP on improved tomato yield at Maseno may partly be attributed to secondary factors other than P, viz; alleviation of aluminium rhizotoxicity since the Al content was significantly reduced by RP treatment, while RP may have led to partial alkalinization at specific root/rhizoplane, leading to Zinc deficiency at Kibwezi site. The application of rock phosphate in addition to acidifying nitrogenous fertilizer with consideration to soil types has potential of improving crop production and phosphate capital of resource-poor farmers.

Key words: Nitrogen forms, r-phosphate, soil-types, tomato

INTRODUCTION

Extensive tracts of land in the tropical and sub-tropical regions of Asia, Africa and Latin America contain highly weathered and inherently infertile soils. These areas generate low crop yields and are prone to land degradation as a result of deforestation, overgrazing and inefficient farming practices. Apart from socio-economic factors, the main constraints are soil acidity and low inherent nitrogen (N) and phosphorus (P) fertility [1]. While N inputs can be obtained from sources such as BNF (Biological nitrogen fixation), crop residues and other organic sources, P inputs need to be applied in the farms in order to improve the soil P status and ensure normal plant growth and adequate yields. Therefore, substantial P inputs are required for optimum growth and adequate food and fibre production [2]. Water soluble phosphate (WSP) fertilizers such as superphosphates are commonly recommended for correcting soil P deficiencies. However, most developing countries import these fertilizers, which are often in limited supply and represent a major outlay for resource-poor farmers. In addition, intensification of agricultural production in these regions necessitates the addition of P inputs not only to increase crop production but also to improve P status in order to avoid further soil degradation. Nutrient efficiency can be enhanced by targeted breeding through pyramiding efficiency mechanisms in a desirable genotype as well as by gene transfer and manipulation [3]. However, this is a long-term venturewhich is not always reproducible and little progress has been reported in plantae. Therefore, it is imperative to explore alternative P inputs. In this context, under certain soil and climate conditions, the direct application of rock phosphates (RPs) has been discussed as an agronomic and economically sound alternative to the more expensive superphosphates in the tropics [4,5, 6]. The direct application of rock P is an avenue to low input agriculture which fits well with emerging Green Revolution for Africa. The direct application of ground, natural RP as a source of P for crops is a practice that has been utilized with varying degrees of success over years. Numerous field and greenhouse experiments have been conducted to assess the capabilities of these materials to supply P to crops and to define the most favourable conditions for their application. The results obtained have been reported as erratic and sometimes conflicting, leading to confusion and disagreement on the utilization of RPs [7]. The main reason for this stemmed from the lack of understanding of the various factors affecting the agronomic effectiveness of RPs. Since the work of Kwasawneh and Doll [7], significant progress on evaluation of the main factors affecting agronomic effectiveness of RPs has been reported. These authors examined and summarized the influence of the inherent RP factors as: Soil factors (pH, texture, organic matter, P status, P fixation and Ca content) and plant factors (growth cycle, P demand and pattern of P uptake, root system and rhizosphere properties). It is now known that plants can enhance the dissolution of RP by acidification of the rhizosphere and high uptake of Ca [8], secretion of organic acid anions that complex Ca [9], and depletion of P in soil solution. The rhizosphere pH changes are attributed to imbalances in cation –anion uptake [10]. Accordingly, nitrogen plays a prominent role in the cation-anion balance because it is the nutrient that is taken up at the highest proportion by most plant species [10, 11]. Root-induced acidification of the rhizosphere, or more precisely the H^+ release that originates in the roots, can thus

dramatically increase the bioavailability of inorganic P whenever Ca phosphates are present, mostly in alkaline to mild acidic soils. Its effect in soils, which have an acidic pH, is more questionable, except when a source of Ca phosphates such as phosphate rock is added to the soil [12, 13]. In order to minimize phosphorus fixation in the soil, localized application methods (such as banded or side dressing) of phosphorus fertilizers are commonly recommended in practice [14]. The above conflicting reports expressed by previous authors [7, 15, 16, 17] prompted need to investigate the benefits of RP under various soil types.

The current research work attempts to investigate perspectives for use of rock phosphate (RP) fertilizers in tomato (*Lycopersicon esculentum* Mill) var Moneymaker cultured in Minirhitrons in greenhouse with Arenosol from West Africa and C-Horizon of a Luvisol as well as two contrasting soils (acidic Ferralsol with pH($CaCl_2$) of 4.6 and an alkaline Luvisol, pH 8.1) under realistic field conditions in western and eastern Kenya, respectively and consequently the effects of; different forms and ratios of N (NO_3^-/NH_4^+) and related changes in rhizosphere biochemical pH changes on rock phosphate mobilization and subsequent utilization by tomato as a model plant known for proton excretion potential [10, 17, 18].

MATERIALS AND METHOD

Minirhizotron experiments at Univesitaet Hohenheim

Plant pre-culture

Seeds were disinfected with 30% H_2O_2 for 15 min, rinsed with tap water, soaked in 10mM $CaSO_4$ for 4h and pre-germinated in wet filter papers containing 2.5 mM $CaSO_4$ in the dark at 25°C. After 5 days, they were transferred to light for one day and then planted in pots containing 2.5L of aerated half-strength nutrient solution (10 plants per pot) in a growth chamber with a 16/8 h light regime at constant temperature of 25°C with light intensity of 150µmol m^{-2} s^{-1} and relative humidity of 60%. After 5 days the concentration of nutrients was doubled to full strength. The composition of solution was: 5 mM Ca $(NO_3)_2$, 1.75 mM K_2SO_4, 1.25 mM $MgSO_4$, 0.25 mM HCl, 1.5 µM Fe (III)-EDTA, 25 µM H_3BO_3, 1.5 µM $ZnSO_4$, 0.5µM $CuSO_4$, 0.025µM $(NH_4)_6Mo_7O_{24}$ and 0.25 mM KH_2PO_4.

Plant transfer to rhizoboxes

After 4 weeks, the seedlings were transferred to the rhizoboxes containing 2.4 kg of either P-deficient acidic Arenosol from Niger, West Africa or C-horizon of Luvisol. Arenosols were characterized by Fe/Al-P as dominant sparingly soluble P-fraction and contained PCAL (5.0 mg Kg^{-1}) while Pbray1 was 7.0 mg kg^{-1} soil andit had pH [pH$Cacl_2$] of 4.5 and organic carbon or Corg [%] of 0.16. On the other hand, the C-horizon of Luvisol (C-loess) was characterized by Ca-P as dominant P with PCAL (3.0 mg Kg^{-1}) while Pbray1 was 2 mg kg^{-1} soil and it had pH [pH$Cacl_2$] of 7.6 and organic carbon or Corg [%] of 0.3.

Fertilisation
N: 100mg/kg soil as $(NH_4)_2SO_4$, $Ca(NO_3)_2$, or NH_4NO_3; K: 150mg/kg soil; Mg: 50mg/kg soil Soluble P: $(Ca(H_2PO_4)_2)$ 80mg P/kg soil; Rock phosphate: Hyperphos 1.5g/kg = 200mg P/kg soil

DMPP (nitrification inhibitor) was added to ammonium treatments 4µl kg^{-1} soil. Soil moisture level was maintained at 15% in the greenhouse culture experiment. The fertilizer was homogeneously mixed and the rhizoboxes were filled. One tomato seedling was transferred to the rhizobox and put in a room with diffuse light for 2 days to adjust to transplanting shock. Thereafter they were taken to the green house and randomly arranged on the benches on stand such that they were inclined at an angle of 50 degrees to allow roots grow towards the window for ease of tracing and taking of pH values.

Field site and experimental set up
Location
The research was undertaken at Maseno and Kibwezi field stations in Kenya.
Maseno is close to Ochinga farm ($0^0$06'N, $34^0$34'E) and has two growing seasons with yearly mean rainfall of about 1800mm. The soil at Ochinga is classified as an acidic Ferralsol (World Reference Base) or as a very fine, kaolinitic, *isohyperthermic Kandiudalfic Eutrudox* (Oxisol) in the USA Soil taxonomy [19]. While the other experiment was conducted at the University of Nairobi Dryland Research Field Station located at Kibwezi in Eastern Kenya, on altitude 2 degrees 17'00"S and Longitude 38degrees 36'36"E. Soil type at this site is a deep Luvisol with good drainage and sandy clay to clay texture [20].

Plant culture
Tomato (*Lycopersicon esculentum*, cv. Moneymaker) plants were pre-germinated in nursery and later (about 35-40 Days after emergence -DAE) transplanted to the fields, which had previously been cultivated to a fine tilth. The inter- and intra-row spacings were both 0.5 m, while the distance between each block was 1.0 m. The plot measured 2.0 m by 3.0 m. After fertilization, seedlings were transplanted and watered adequately.

Fertilization
In band placement the nutrients were thoroughly mixed with 2 kg of dry soil from holes dug 12 cm deep with diameters of about 17 cm around the plant; while in deep placement, fertilizers were applied directly below the roots into the planting holes, mixed with 1kg of soil from the same horizon as for band placement and mixed with the nutrients. The Plan for field experiments was completely randomized block design (CRBD) having split plot with main plots as P_0 (no P supply), rock P (rock phosphate supply) and soluble P (Water soluble P supply) and different forms of N: NO_3^-, NH_4^+ and NH_4NO_3 formed the subplots and these N treatments were randomized within the P treatments.

Plant Harvest

Plants were harvested from the two middle rows (there were 4 rows per plot) and sampling was stratified to avoid random gaps. After washing the roots, the shoots were separated from the roots and placed in different paper bags. Fruits were also separated and placed in different paper bags. Before plant parts were placed in different paper bags, they were put between sorption papers and slightly pressed to remove water before fresh weights were recorded. Subsequently, the plant materials were oven-dried at 75^0C for 3 days and dry weights recorded.

Sample preparation and mineral analysis

Harvested samples were washed and gently pressed between sorption papers to drain water, after which fresh weights were recorded. The samples were placed in the oven at a temperature of 65^0C for 3 days to dry. Sometimes the dried samples were re-dried and then ground into fine powder of 0.2mm. Analysis of mineral nutrients in shoot tissues was performed after dry-ashing of the plant material at 500°C for 4 h in a muffle furnace. After cooling, the samples were extracted twice with 2 ml of 3.4 M HNO_3 (v/v) till dryness to precipitate SiO_2. The ash was dissolved in 2 ml 4 M HCl, subsequently diluted 10 times with hot deionised water and boiled for 2 min. After addition of 0.1ml Cs/La buffer to 4.9 ml ash solution (for Mn and Fe), while for P, colour reagent (molybdate-vanadate-solution) was added. Mineral elements were determined by atomic absorption spectrometry (Al, Zn, Ca, and Mg), flame photometry (K) and spectrophotometry (P).

RESULTS

Minirhizotron experiments

There were striking differences in growth between nitrate and ammonium treated plants irrespective of P supply. The results showed consistent shoot biomass reductions associated with NH_4-N nutrition as compared to NO_3^- supply (Figs. A and B).

However, when NO_3^- was added to NH_4^+ and supplied in form of NH_4NO_3 in 1:1 ratio, the shoot biomass inhibition observed with sole ammonium was alleviated. There was also a corresponding negative effect of sole NH_4-N form on root growth (Fig.1A and B).

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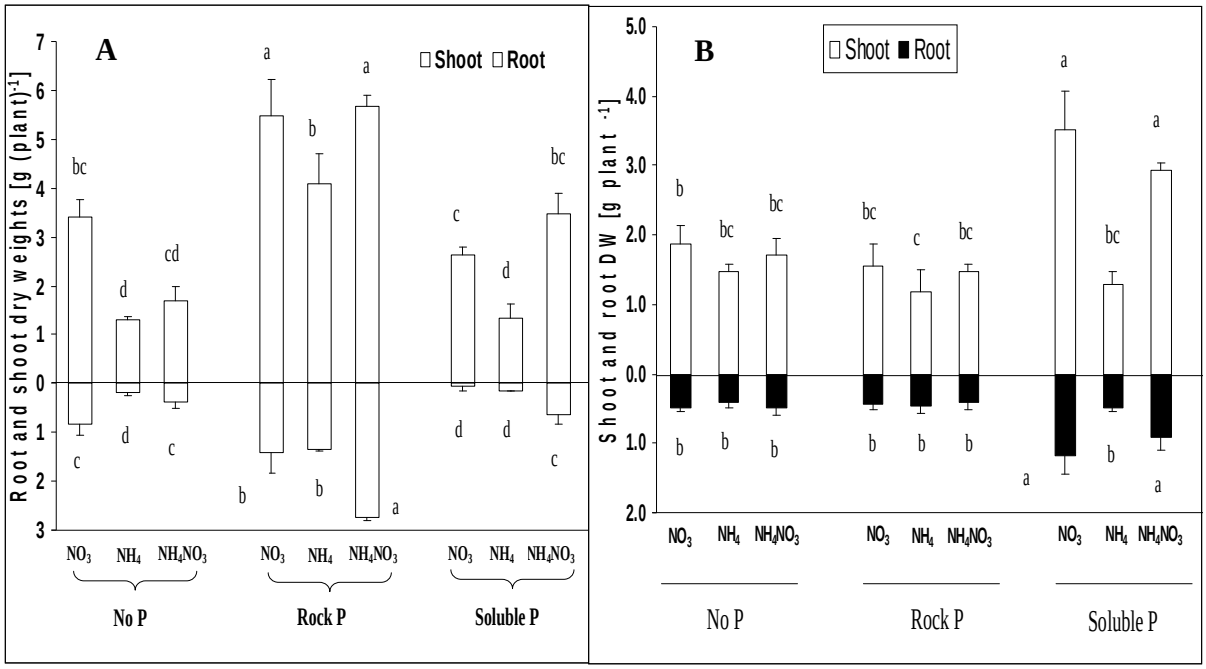

Figure 1: Plant biomass of tomato grown in rhizoboxes filled with Arenosol (A) and C-horizon of Luvisol (B) as affected by nitrogen and P forms. Plants were harvested 35 Days after transplanting (DAT). The bars represent SD, n=4, p≤0.05.

Plants cultured without P supply exhibited early symptoms of P deficiency as reflected by inhibited shoot growth and anthocyanin formation as was evidenced by visual purple coloration of the shoots. It is highly unlikely that tomato plants were able to utilize P from Al/ Fe-P dominant Arenosol from West Africa. On the other hand, plants receiving rock phosphate had better growth and were even superior to soluble-P treated variants (Fig.1A).

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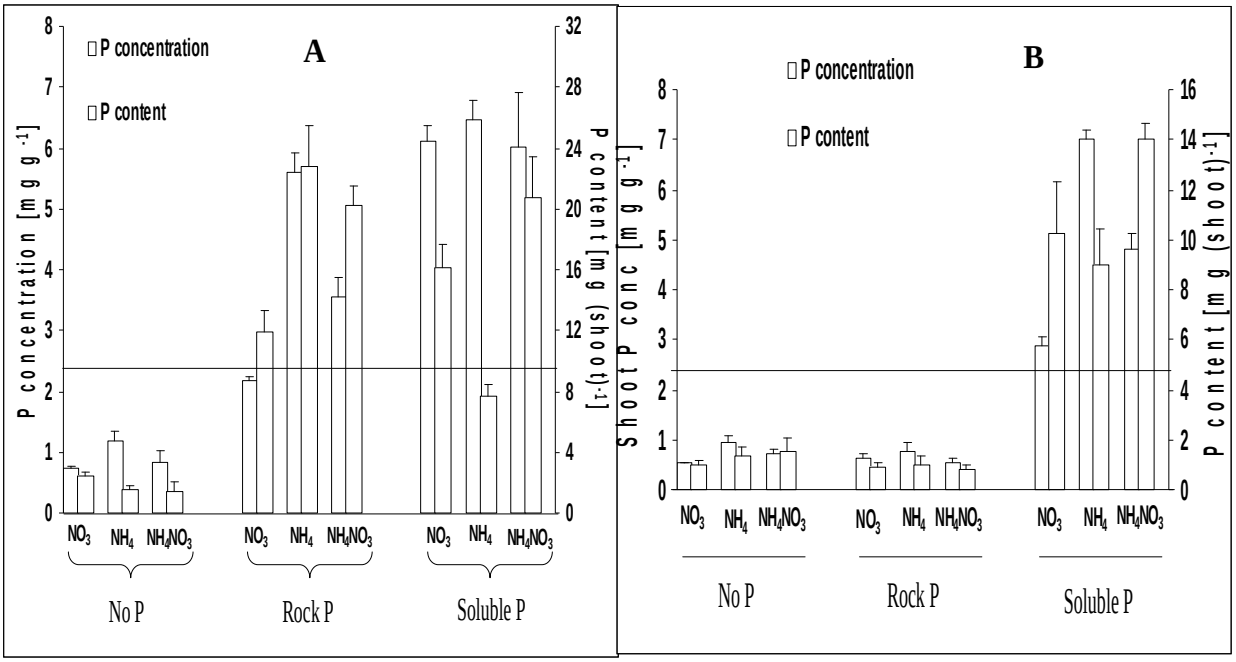

Figure 2: Tomato shoot P concentrations and contents as influenced by nitrogen forms and P supply (No P, rock P and soluble P): A greenhouse experiment with rhizoboxes supplied with Arenosol (A) and Luvisol -C-loess (B) soil cultures. Plants were harvested 35 DAT. Dotted line represents P critical concentration. Error bars based on n=4.

Irrespective of P source, the NH_4-N treated variants consistently accumulated relatively lower biomass as compared to other N treatments. Tomato plants supplied with rock phosphate similarly exhibited stunted growth and had purple coloration of the leaves under Luvisol soil substrate (Fig. 1B). In contrast to plants grown in the Arenosol culture (Fig.1A), rock P had no positive effect on biomass formation of tomato plants grown on the Luvisol. Only soluble P with N as NH_4NO_3 or $Ca(NO_3)_2$ showed improved plant growth (Fig.1B). In agreement with plant growth in the Arenosol (Fig.1A), NH_4-N supplied plants in the Luvisol with soluble P had poor biomass formation as compared to either sole nitrate or ammonium nitrate supply. There was, however, no significant influence of N forms on root biomass of the plants that received rock phosphate or no P. On the other hand, with soluble-P supply, tomato plants supplied with NH_4-N had significantly lower root as well as shoot biomass compared with sole NO_3^- or NH_4NO_3 application.

Plant tissue P concentrations for plants that received no P were below critical level as shown in Fig.2A under cultivation with Arenosol. The plants receiving phosphate rock had higher tissue P concentrations and contents and were even superior to soluble-P. Interestingly, ammonium treated plants, in spite of smaller shoot biomass,

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had the highest tissue concentrations as well as contents. There was a corresponding but negative relationship between rhizosphere pH and plant P status (Fig.2 and Table.1). Similar trends were observed in Plant Al tissue concentrations and contents, where NH_4^+ treatments led to accumulation of Aluminium (Table.1). This concentration was, however, below the toxic range for tomato plant [21].

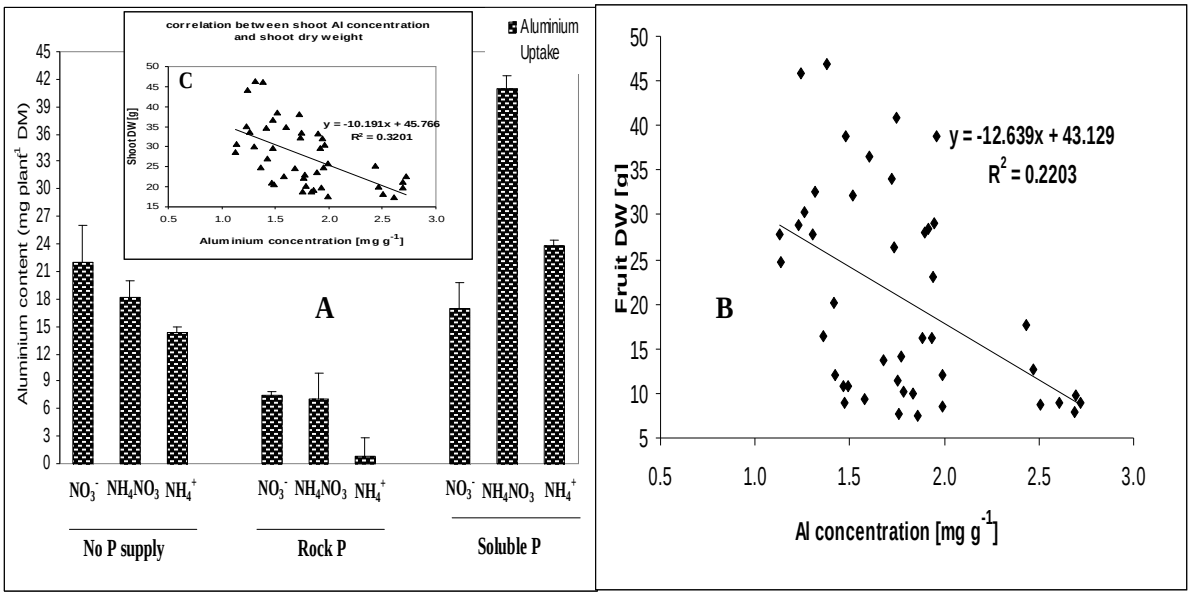

Figure 3: Tissue Aluminium uptake between 29 and 46 DAT (A), correlation between tissue Aluminium concentration and fruit dry matter (B) and correlation between Aluminium concentration and shoot dry matter (C inset) – Maseno site, Kenya.

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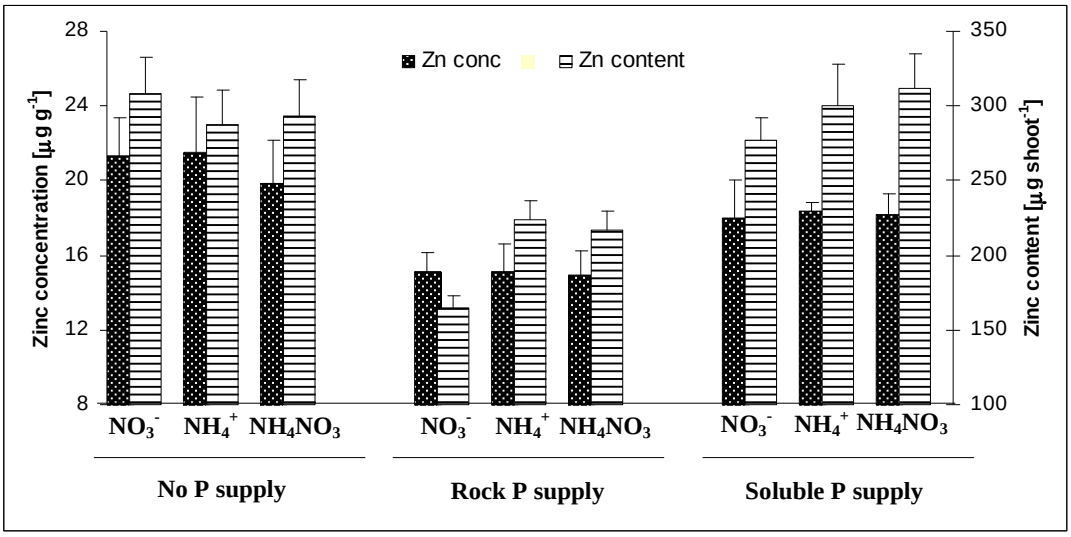

Figure 4: Plant tissue zinc status of tomato plants grown on Luvisol at Kibwezi site – Kenya. The plants were supplied with different forms of nitrogen and received rock P, soluble P or P was omitted. Tissue P was determined on plants harvested at 45 DAT.

However, with Luvisol substrates, plant shoot P concentrations and contents were significantly affected by P supply. There were no significant differences between rock P treated plants and those receiving no P. Except for the treatment with soluble P, all treatments had their P concentrations below the critical levels of 2.3mg P/g DM (Fig.2B). With supply of soluble P, the adequate nutritional status of the shoots was reached. Plant P content corresponded with plant biomass (Figs 1B and 2B). The results confirmed that P was the main limiting growth factor when plants were grown with rock phosphate in the calcareous Luvisol. In contrast to the Arenosol substrate (Table.1) where ammonium nutrition elicited a strong rhizosphere acidification with subsequent solubilization of rock P, this relationship could not be demonstrated with plants grown in the calcareous Luvisol.

Field experiment

Rock phosphate treatment elicited significantly greater shoot biomass accumulation as compared to soluble phosphate as well as for the variant with no phosphate supply at Maseno site. During third harvest (46 DAT), among the rock phosphate variants, NH_4NO_3 treatments resulted in a significantly higher shoot biomass as compared with either sole NH4-N or NO_3-N treatments (Table.2). This trend was observed throughout the three harvest periods. Irrespective of nitrogen form supplied, all the P treatments (soluble P, Rock P or no P) supply showed no statistical differences in

shoot tissue concentrations of phosphorus, Ca, Mg, and also for K (Table.2) but there were differences in shoot mineral contents between these P treatment due to differences in biomass. The trends in plant tissue Manganese and particularly Aluminium contents were interesting. Plants cultured either without P or receiving soluble P showed less declining tissue contents of Al between 29 and 46 DAT as compared with plants treated with RP.. Plants supplied with RP also showed a significantly lower increment of Al accumulation in the shoot tissue compared to the remaining treatments (Fig.3A). The results also showed a negative relationship between tissue Al concentration and fruit biomass (Fig.3B) and also between Al concentration and shoot biomass (Fig.3C).

Contrary to the results on the Ferralsol at Maseno, rock phosphate did not contribute to a better biomass accumulation on this calcareous Luvisol. Instead there were negative growth responses related to RP (Table.2). This was evident at final harvest in RP treated plants supplied with sole NO_3-N and in instance when RP was locally placed close to the roots. Micronutrients such as manganese, zinc and iron are known to limit plant production on calcareous soils [10]. The results indicated critically low shoot tissue Zn concentrations (< 20 µg g^{-1} DM) for all treatments during the whole growth period, with particularly low levels for plants supplied with RP placement (Fig.4).

DISCUSSION

The lack of plant shoot biomass accumulation without P supply indicates that there was no P-acquisition from native Fe/Al-P forms in the acidic Arenosol, probably due to lack of significant P deficiency-induced root exudation of carboxylates, as earlier reported for model experiments in nutrient solution [18]. Furthermore, P deficiency-induced root exudation of carboxylates was not observed in tomato [18] but mainly release of protons [17, 22]. Contrary to the results with Arenosol soil culture, use of RP under C-loess soil was not observed, as biomass production was comparable to minus P. Despite the highest P concentrations and P contents (Fig.1B) and particularly for soluble P supply, root and shoot growth of the NH_4^+ treatments was depressed (Figs 1A). Aluminium concentrations in the shoot tissue ranged from 0.09-0.17 mg/g dry matter (Table.1) in all treatments, suggesting that increased solubilization of toxic Al species by intense rhizosphere acidification and limited Al exclusion were not responsible for growth depressions observed in the NH_4^+ treatments on the acidic Arenosol soil culture. Similar biomass reductions were also observed with C-loess (Fig. B), despite this soil not being associated with Al saturation.

Extremely low nitrogen levels are a common feature of both Arenosol and C-horizon of Luvisol soils used for these experiments. The present data suggest that in this case, exclusive ammonium nutrition supplied with nitrification inhibitors may induce growth inhibition due to reduced production of cytokinins and increased levels of ABA(Absciscic acid) [23] and other metabolic disorders related with the absence of nitrate and ammonium toxicity for case of the Arenosol and C-horizon of Luvisol.

Acidification resulting from decomposition of organic substances has partially been attributed to beneficial role of rock P under differing soil types [5]. The benefits observed by these authors were noticeable with melons during first year but the effects with maize were observed only during second season. Proton extrusion by maize roots was marginal and benefit was mainly from acid humic substances after adequate mineralization period. Both soils had equally lower buffer capacity.

Rhizosphere pH has a strong influence on extractability and consequently on plant availability of Pi, as shown since the early work of Riley and Barber [24]. These authors [24] also found that concentration of P in the shoots increased linearly with decreasing pH. This is in agreement with the results of Arenosol soil culture, particularly in case of rock phosphate treatments (Fig.2B and Table.1). Gahoonia *et al.* [15] also reported that ryegrass fed with NH_4^+ took up more Pi (orthophosphate) from a Luvisol than when fed with NO_3-. They showed that plants supplied NH_4^+ resulted in a steep rhizosphere acidification and in a larger depletion of HCl-extractable P (phosphorus) than plants fed with NO_3-, which alkalinized their rhizosphere. Bertrand *et al.*, [16] showed that the depletion of HCl-P in the rhizosphere increased with increasing rhizosphere acidification. The current results with C-loess (C-horizon) of Luvisol, despite acidification of rhizoplane, there was no corresponding increase in tissue P concentration as reported above [16]. Obviously the pH buffering capacity of Luvisol was strong due to high free $CaCO_3$ content, leading to negligible or no measurable pH changes in the rhizosphere 2mm away from the root/soil interface (Table.1).

Whole shoot and fruit dry weights on the acid soil at Maseno site were increased by RP treatment irrespective of the N form supply. The lack of impact of N forms may be due to the high buffering capacity and already too low pH that the contributions of H^+ or OH^- eventually were not, in this regard, of great effect. Plant tissue P, Ca Mg and K (Table.2) concentrations were all in sufficient ranges and, thus, could not explain the differences in shoot and fruit dry weights suggesting that RP treatments affected another growth limiting factor. Though RP contains substantial amount of Ca besides P, its solulization had no additional benefit of Ca to plants at the Maseno site. Such interesting observation was reported in previous experiment with tomato [17] where rhizosphere acidification was inversely related to plant Ca but positive to P content. The authors attributed this to nonspecific inhibition of Ca, at uptake site by ammonium ions.

Another indirect role of RP was observed on the calcareous Luvisol in Kibwezi with the main difference between P treatments, particularly with RP in combination with NO_3 applications exerting negative effects on biomass production. Possible causes for the observed P-independent effects of RP applications on tomato growth and yield formation are discussed below.

From current field experiments, there was no growth inhibition (Table.1) as a result of sole ammonium nutrition as was observed in rhizobox experiments. It had previously been hypothesized that exclusive ammonium nutrition supplied with nitrification

inhibitors may induce growth inhibition due to reduced production of cytokinins and increased levels of ABA [19] and other metabolic disorders related with the absence of nitrate is ammonium toxicity. Again, biomass of plants cultivated at Maseno showed lowered Al uptake when supplied with rock phosphate (Fig.4). Aluminium toxicity is a common stress factor in acid soils and can be alleviated by increasing soil pH using lime application [25] or by supply of organic matter with the ability to detoxify Al_3^+ by complexation. Interactive role of sufficient P supply and tissue aluminum have recently been elucidated [26], and in the current study, though tissue P concentration was similar to other P treatments, RP treatments had higher P tissue contents (dilution effects led to possible lowered concentrations). The observed lowered P concentration resulting from higher shoot and fruit biomass further explains beneficial role of RP in acid Ferralsol at the Maseno site.

Micronutrients can be a limiting factor in plant growth on calcareous soils. Accordingly, the results at Kibwezi showed a low Zn-nutrient status for all treatments and strong Zn deficiency, particularly with RP, especially when placed locally or when in combination with NO_3-N during initial stages of growth. Calcareous soils tend to be low in organic matter and available nitrogen. The high soil pH resulted in phosphorus being unavailable and, frequently, zinc and iron can be deficient. Thus Zn limitation may explain the trend for lower biomass production observed in the RP treatments with NO_3^- nutrition (Fig.4 and Table.2), where a nitrate-induced increase in rhizosphere pH and/or a buffering effect of high local RP concentrations close to the roots may further reduce Zn availability. The results from the four soil types strongly indicate variable potential benefits of rock P in tomato production.

CONCLUSION

Tomato plant was able to utilize rock phosphate under different soil situations, with Arenosol being the best candidate due to its low buffer capacity, while it was not effective under Luvisol, both in minirhitron and field situation at Kibwezi. On the other hand, rock P was effective at Maseno. Therefore, if applied with consideration of site specificity coupled with rhizosphere management (though different N supply), rock P can offer alternative source of P and hence directly or indirectly help in improving P capital with consequent improved yield by resource-poor farmers.

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Table 1: Plant tissue Aluminium status of tomato plants cultured on rhizobox, bulk soil, rhizosphere pH variations as affected by phosphorus supply and nitrogen forms in Arenosol and Luvisol. pH measurements were done at 14 DAT (Days after transplant) while tissue aluminium analysis on plants harvested 35 DAT

	No P			Rock P			Soluble P		
	$NO3^-$	NH_4NO_3	NH_4^+	NO_3^-	NH_4NO_3	NH_4^+	NO_3^-	NH_4NO_3	NH_4^+
Plant tissue									
Al_3^+ Conc. (mg/g)	0.15 **(0.01)**	0.7 **(0.03)**	0.12 **(0.05)**	0.09 **(0.00)**	0.01 **(0.04)**	0.13 **(0.04)**	0.12 **(0.05)**	0.15 **(0.03)**	0.13 **(0.00)**
Al_3^+ Content (mg/plant)	0.50 **(0.05)**	0.48 **(0.05)**	0.30 **(0.14)**	0.29 **(0.08)**	0.55 **(0.22)**	0.47 **(0.17)**	0.22 **(0.04)**	0.61 **(0.07)**	0.18 **(0.05)**
Soil pH									
Arenosol									
Bulk	4.08 **(0.15)**	4.85 **(0.19)**	4.88 **(0.13)**	4.55 **(0.25)**	5.23 **(0.15)**	4.78 **(0.13)**	3.91 **(0.06)**	5.13 **(0.10)**	4.33 **(0.10)**
At root tip	3.98 **(0.11)**	4.68 **(0.68)**	4.63 **(0.17)**	3.90 **(0.22)**	4.53 **(0.13)**	3.98 **(0.06)**	3.60 **(0.25)**	4.45 **(0.26)**	3.09 **(0.07)**
Basal root	3.13 **(0.10)**	4.53 **(0.05)**	4.75 **(0.06)**	3.45 **(0.13)**	4.25 **(0.13)**	3.45 **(0.05)**	3.63 **(0.29)**	3.73 **(0.24)**	2 .90 **(0.47)**
Luvisol									
Bulk	7.27 **(0.41)**	7.73 **(0.10)**	7.74 **(0.07)**	7.27 **(0.08)**	7.73 **(0.09)**	7.70 **(0.12)**	7.20 **(0.10)**	7.75 **(0.07)**	7.76 **(0.12)**
At root tip	6.07 **(0.06)**	5.99 **(0.08)**	6.32 **(0.07)**	5.91 **(0.08)**	5.95 **(0.07)**	6.18 **(0.08)**	5.89 **(0.05)**	5.67 **(0.11)**	6.08 **(0.11)**
Basal root	5.66 **(0.13)**	5.74 **(0.11)**	6.48 **(0.09)**	5.68 **(0.04)**	5.93 **(0.23)**	6 .56 **(0.21)**	5.68 **(0.04)**	5.95 **(0.11)**	6 .30 **(0.21)**
2 mm from Root tip	7.12 **(0.09)**	7.28 **(0.49)**	7.50 **(0.11)**	7.19 **(0.03)**	7.46 **(0.12)**	7.50 **(0.10)**	7.19 **(0.03)**	7.50 **(0.08)**	7.50 **(0.02)**
2 mm from Root basal part	7.20 **(0.08)**	7.52 **(0.12)**	7.53 **(0.05)**	7.23 **(0.05)**	7.44 **(0.11)**	7 .52 **(0.09)**	7.15 **(0.05)**	7.58 **(0.11)**	7 .54 **(0.10)**

The bolded values in parentheses represent SD, n=4.

Table 2: Plant biomass and tissue mineral concentrations of tomato plants grown in two soils at Maseno (Ferralsol) and at Kibwezi (Luvisol). The plants were harvested at 46 Days after transplanting (DAT).

	No P			Rock P			Soluble P		
	$NO3^-$	NH_4NO_3	NH_4^+	NO_3^-	NH_4NO_3	NH_4^+	NO_3^-	NH_4NO_3	NH_4^+
Plant shoot DM (g)									
Maseno site	19.8	29.6	19.8	21.2	38.0	26.0	22.2	32.1	22.3
	(2.08)	**(3.55)**	**(1.85)**	**(2.23)**	**(4.92)**	**(2.61)**	**(2.65)**	**(0.96)**	**(2.00)**
Kibwezi site	14.9	10.3	15 .0	17.9	15.3	18.4	16.0	15 3	17.4
	(4.34)	**(1.17)**	**(4.76)**	**(4.31)**	**(3.09)**	**(4.85)**	**(3.83)**	**(2.20)**	**(3.63)**
Plant shoot mineral conc. (mg g^{-1})									
Maseno site									
Phosphorus	2.47	2.23	2.64	2.82	2.11	2.72	2.46	2.33	2.56
	(0.26)	**(0.33)**	**(0.26)**	**(0.54)**	**(0.07)**	**(0.24)**	**(0.19)**	**(0.42)**	**(0.41)**
Calcium	19.0	19.0	17.9	21.0	18.8	18.0	20.5	19.9	17.8
	(2.23)	**(2.49)**	**(3.18)**	**(2.06)**	**2.70)**	**(1.40)**	**(1.41)**	**(1.97)**	**(2.54)**
Magnesium	7.07	6.24	6.55	7.30	6.56	6.84	7.11	6.31	6.44
	(0.47)	**(1.14)**	**(0.92)**	**(1.38)**	**(1.09)**	**(0.51)**	**(1.18)**	**(0.36)**	**(0.91)**
Potassium	24.8	20.0	28.9	25.3	21.7	29.9	25.2	19.5	18 .8
	(2.81)	**(2.54)**	**(6.75)**	**(2.95)**	**3.17)**	**(2.96)**	**(2.53)**	**(2.94)**	**(1.82)**
Kibwezi site									
Phosphorus	4.61	3.72	3.88	4.59	4.34	4.86	4.37	4.42	4.43
	(0.79)	**(0.69)**	**(1.07)**	**(0.91)**	**(0.78)**	**(0.30)**	**(0.49)**	**(1.23)**	**(0.57)**
Calcium	22.3	24.3	24.1	26.1	23.9	24.0	24.2	23.9	27.0
	(2.18)	**(1.37)**	**(3.60)**	**(1.68)**	**(2.78)**	**(2.74)**	**(2.58)**	**(3.06)**	**(4.82)**
Magnesium	7.53	8.65	8.55	9.21	7.68	9.12	7.87	7.37	9 .95
	(0.23)	**(1.87)**	**(1.95)**	**(1.01)**	**(1.32)**	**(1.55)**	**(0.82)**	**(1.78)**	**(1.45)**
Potassium	45.6	41.2	49.5	46.5	44.3	47.1	47.2	42.1	50.5
	(6.34)	**(6.82)**	**(8.95)**	**(1.47)**	**(9.99)**	**(5.92)**	**(4.68)**	**(9.35)**	**(4.92)**

The bolded values in parentheses represent SD, n=4.

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