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Can Phosphate Rock Boost Maize (*Zea mays* L.) Growth under Alkaline Soil Conditions?

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Authors' contributions

This work was carried out in collaboration between all authors. Authors MAE, MMOA and SS designed the study. Author WAM performed the research. Authors MAE and MMOA contributed new reagents/analytic tools. Authors WAM and SS analyzed the data. Author SS wrote the paper. All authors read and approved the final manuscript.

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ABSTRACT

Phosphorus deficiency forms an important constraint for crop production, especially in tropical marginal countries like the Sudan. Unfortunately, the majority of soils in the Sudan are phosphate (Pi) deficient, while chemical Pi fertilizers are not affordable for resource-poor farmers. Thus, alternative fertilization strategies are urgently needed to improve yields of crops, especially on alkaline low-fertile soils. Having some novel and simple solutions can offer tremendous opportunities to protect the environment, rebuild soil fertility, and improve food security in the Sudan and similar countries. Hence, a pot experiment was conducted to study the impact of phosphate rock (PR) on

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the growth performance of maize “line KHM405” grown in two types of alkaline soils differing in the soil physical and chemical properties (clay *vs.* sand-clay-loam). Results obtained showed that the application of PR to clay or sand-clay-loam soil had no significant effect on all examined parameters (plant and soil). Because of the alkalinity of the soil, the present study indicated the importance of future studies to establish efficient methods of partial acidulation to improve the solubility of phosphate in the PR materials.

Keywords: Calcareous soil; maize; phosphate rock; phosphorus deficiency.

1. INTRODUCTION

Sudan, officially the Republic of Sudan but sometimes referred to as North Sudan, is one of the greatest countries in Africa and Arab world in terms of land area. It has around 40 million people and massive agricultural resources of approximately 17.1 million ha arable land [1]. It is envisaged that the Sudanese population will extend to increase in the next few decades, while average arable land will continue to decline. Clearly, food security in the Sudan will be of a top priority in international development over the next decades (sudan@fews.net). Options to enhance food production are limited because most arable land is already under cultivation, and in many areas agricultural land has been greatly minimized due to industrial development and urbanization [2].

Recently, the Sudanese Government has taken a new strategic approach to support agriculture and embrace a more thriving future for the inhabitances in a sustainable basis. This is because Sudan’s economy was strongly affected when it lost 75% of its oil revenue following the secession of South Sudan in 2011 (http://www.wfp.org/countries/sudan). Consequently, new marginal areas with low fertility have been brought into production. However, a primary constraint to crop production in such infertile soils is low phosphate (Pi) availability [3-5]. Pi deficiency is very common on alkaline calcareous soils due to formation of insoluble calcium Pi compounds. With the potential exception of nitrogen (N), phosphorus is frequently the most important limiting factor for plant growth and development in the Sudan [6]. Modern Sudanese agricultural practices have sought to resolve this puzzle through the application of Pi, in the form of chemical fertilizers. This was a primary concern of several researchers in this agrarian country who were able to point out the positive response of numerous crop species to chemical Pi application [7-9]. Unfortunately, the chemical fertilizers are expensive and remarkably raise the overall cost of production [10,11]. Furthermore, large-scale implementation of Pi-chemical fertilizers may cause heavy pollution and eutrophication of water systems leading to serious environmental implications. Not surprisingly, the mitigation of excessive Pi losses to surface waters is currently a global concern (http://www.unep.org/). Chemical-Pi fertilizers are produced using finite, non-renewable high-quality Pi rock (PR) sources. Based on some estimates, available PR is expected to deplete during the 21st century [12-14]. This will result in significantly increased cost, particularly for developing countries, such as the Sudan. Hence, to ensure future high levels of agricultural productivity in this country, it will be indispensable to find out some potentially locally available Pi sources.

The use of PR as a source of Pi for plants has been recognized for quite long time [15]. PR is the raw material in the industrial manufacture of water-soluble Pi (WSP) fertilizers or as a low cost fertilizer for direct implementation in agriculture [16]. In support, prosperous application of PR in agriculture has notably enhanced soil Pi levels [17] and the efficiency of PR sometimes equalize WSP fertilizers, depending on the quality and chemical ingredients of the PR used [18]. Unfortunately, this finite, non-renewable resource is becoming increasingly scarce as explained above. Unlike the situation in many other countries, several types of PR deposits have been discovered in the Sudan.

Since PRs are relatively cheaper and sufficiently available in the Sudan, therefore, the main objective of the present study was to evaluate the agronomic effectiveness of maize in response to these local-Pi resources under conditions of alkaline soils. The evaluation was based on using triple superphosphate (TSP) as a positive control.

2. MATERIALS AND METHODS

2.1 Site Description

The study was carried out in the Experimental Farm of the Faculty of Agriculture, University of Khartoum (latitude 15° 40' N, longitude 32° 32' E and altitude 386 meters above sea level) at Shambat during the winter season of 2014/2015. The climate of the locality is tropical semi-desert with low relative humidity. The mean annual rainfall is 160 mm with a mean maximum temperature above 40°C and around 20°C during the summer and winter seasons, respectively. Solar radiation is about 400–500 cal cm^{-2} day^{-1}.

2.2 Soil Characteristics

Two types of alkaline soils were used in the present study: clay soil from Shambat area (referred as *clay* soil) and sand-clay-loam soil from El-Rawakeeb Dry Land Station located west of Omdurman (referred as *sand-clay-loam* soil). El-Rawakeeb Station lies around 45 Km from the capital Khartoum, between latitudes 15° 22' and 15° 36' N and longitudes 32° 0' and 32° 10' E, and 420 meters above sea level [19]. The climate of the area is a part of the arid and semiarid zones with a low relative humidity (< 20%). The summer is hot and dry, and the winter is moderately cold and dry. The temperature ranges between 40°C (maximum) in summer and 21°C (minimum) in winter. The rainy season starts in July and ends in September. The average rainfall is approximately 157 mm. The physical and chemical properties of the two types of soils are presented in Table 1.

2.3 Plant Material and Growth Conditions

Seeds of maize (*Zea mays* L. 'line KHM405') were sown at a rate of five seeds per pot in 5 liter black plastic bags containing the above mentioned soil substrates. Thinning to two seedlings per pot was carried out, two weeks after sowing. Representative soil samples from the upper (0–20 cm) layers of the two soil types were collected and composited using core samplers. Thereafter, the soil samples were sterilized at 120°C (90 min) using an electric oven to destroy any possible indigenous microorganisms in the soil. For improvement of physical characteristics, Shambat soil samples were primarily mixed with 0.5 kg sterilized sand for each pot before the seeds were sown. The pots were arranged in a Completely Randomized Design (CRD) with four replicates for each treatment. Prior to sowing, all pots were irrigated with tap water followed by watering three times a week for both type of soil. Based on the field capacity, the estimated volume of water per day was ~ 400 mL for clay soil and ~ 500 mL for sand-clay-loam soil, pending on the plant age and the climatic conditions i.e., daily temperature. Plants were harvested at 85 DAS (days after sowing), and shoot and root dry matter were determined.

2.4 Treatments

The treatments consisted of two levels of PR (0 and 227.3 t ha^{-1}) and two types of soils: clay (Shambat) and sandy-clay-loam (El-Rawakeeb). The PR used in the present study was obtained from Kurun deposit, Nuba Mountain (Fig. 1, Table 2). Triple superphosphate (TSP; 48% P_2O_5) was included as positive control in a dose

Table 1. The physical and chemical properties of the topsoil (0–20 cm) and subsoil (20–40 cm) used in the pot experiment

Properties	**Clay**		**Sand-clay-loam**	
	0–20 cm	**20–40 cm**	**0–20 cm**	**20–40 cm**
pH (paste)	7.7	8.2	7.2	7.6
EC_e (dS m^{-1})	1.13	1.40	0.67	0.70
Ca (meq L^{-1})	2.10	2.50	2.00	2.50
Mg (meq L^{-1})	1.00	1.30	1.00	1.50
N_t (%)	0.02	0.05	0.02	0.02
P (ppm)	0.57	0.82	0.41	0.52
K (meq L^{-1})	0.22	0.50	0.25	0.80
Particle size distribution:				
Sand, %	29.9	24.0	47.0	56.0
Silt, %	24.4	27.0	15.8	11.0
Clay, %	45.7	49.0	37.2	33.0

N_t, total nitrogen

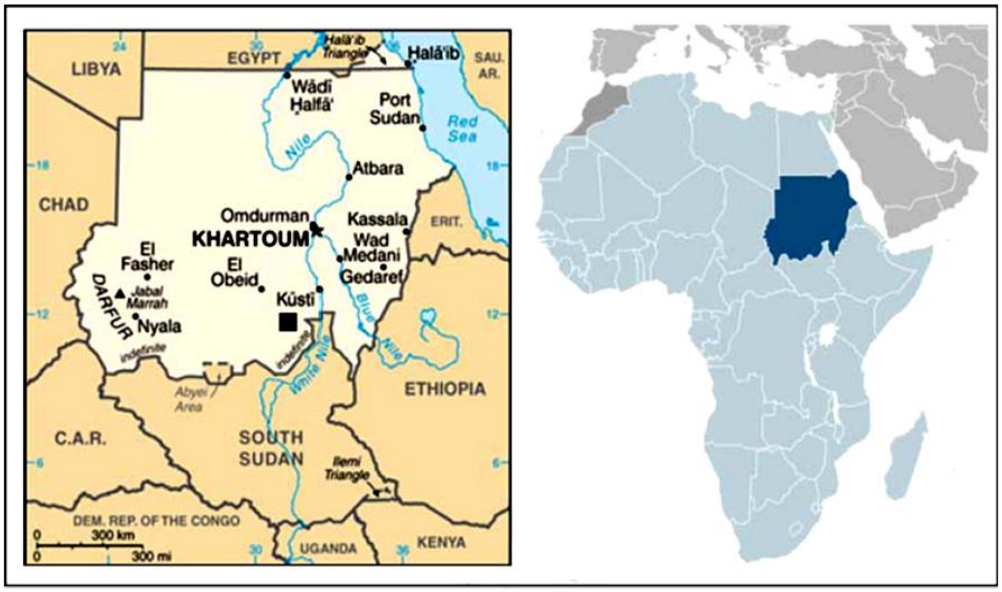

Fig. 1. Map of the Sudan showing the location (■) of Kurun rock phosphates

Table 2. Summary of the major elemental percentage in the PR used in the study

P_2O_5	CaO	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	CO	SiO_2	SO	Zn	MnO	Cu
						(%)						
26.2	28.0	12.0	4.0	0.3	0.2	0.8	6.2	14.0	1.0	0.4	0.4	0.2

equivalent to 50 kg P_2O_5 ha^{-1}. A basal N dose of 18 kg N fed^{-1} was applied to all pots two weeks after sowing (i.e., after thinning), and another similar dose was provided at 63 DAS. Urea (46% N) was the source of N in the experiment.

2.5 Analytical Determinations

Soil analyses were done at the end of the experiment (after harvest). The soil samples were collected from the root zone (i.e., rhizosphere) by gently brushing the roots after the plants were pulled out and the roots were separated from the shoot fractions. The soil samples were air-dried and ground to pass a 2.00 mm sieve. Soil pH was measured in saturation 1:1 soil/water paste by pH meter (Jenway 3510, Bibby Scientific Ltd., UK). The electrical conductivity of the extract (EC_e) was obtained by 470 cond. meter (UK). N was determined by the micro-Kjeldahl method, whereas Pi content was determined calorimetrically by the Vanadate-Molybdate-Yellow method. Potassium (K) was measured by the flame photometry (Jenway PFP7, Bibby Scientific Ltd., UK), while calcium (Ca), magnesium (Mg) were determined by titration [19]. Apart from the soil analyses, contents of the PR samples were determined by the X–ray Fluorescence Spectrometry.

2.6 Statistical Analysis

The recorded data were subjected to the analysis of variance (ANOVA), and means were separated by using the Least Significant Difference ($LSD_{5\%}$). All statistical analyses were conducted using statistical tools imbedded in Microsoft Excel (2007).

3. RESULTS AND DISCUSSION

PR, a naturally occurring mineral source of insoluble Pi is a cheap source of phosphorus for plants but cannot be used directly as a soil amendment because of its very poor water solubility [4,7]. Accordingly, maize 'line KHM405' was grown in two types of alkaline soils differing in the soil physical and chemical properties (Table 1). The growth of plants was characterized in term of dry matter accumulations for the shoot (Fig. 2a) and root (Fig. 2b) fractions. Leaf protein (Fig. 3) and mineral nutrients (N, Pi, K, Ca, Mg; Table 3) and rhizospheric soil chemical analyses (pH, EC_e, mineral nutrient contents; Table 4) were performed at the end of the experiment. Results obtained show that the application of PR and TSP to both alkaline soils has insignificant response for all examined growth and chemical analyses (plant and soil).

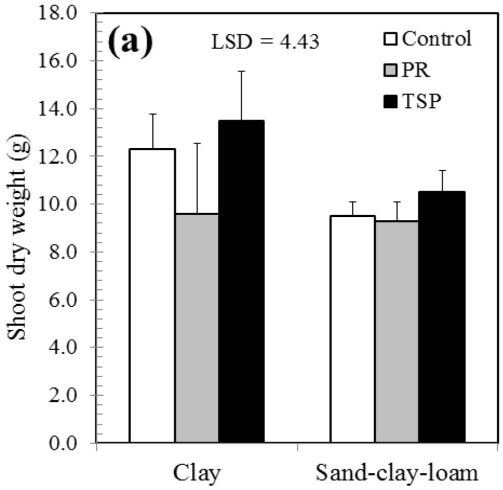

Fig. 2a. Impacts of phosphate rock (PR) and triple superphosphate (TSP) on the shoot dry matter accumulation for maize grown on clay or sand-clay-loam soil. Bars ±standard error of four replicates

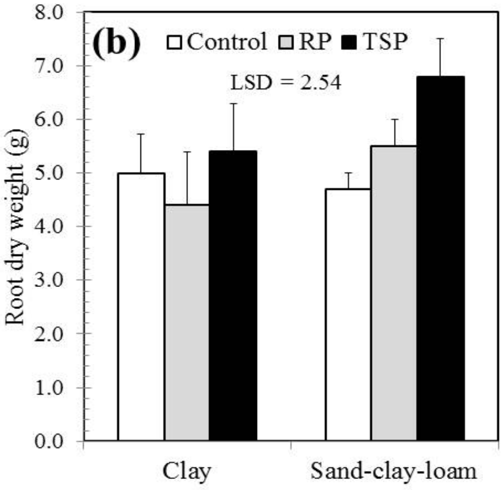

Fig. 2b. Impacts of phosphate rock (PR) and triple superphosphate (TSP) on the root dry matter accumulation for maize grown on clay or sand-clay-loam soil. Bars ± standard error of four replicates

3.1 Effect of PR Application

Soil properties can affect the suitability of PR for direct application [7,20]. Factors affecting PR dissolution and efficiency in soil include, but not limited to, pH, cation exchange capacity (CEC), Ca and Pi concentrations, Pi-sorption capacity, and organic matter (OM) content. Dissolution of apatite is dependent on the neutralizing reaction between H^+ concentrations and the apatite content in PRs. Acid soils and acid-generating processes, as well as inorganic and organic acids, all contribute to enhanced PR dissolution at low pH. Acid soils and acid-generating processes, as well as inorganic and organic acids, all contribute to enhanced PR dissolution at low pH. Thus, the insignificant response of PR revealed in the present study might be related to the alkaline nature of soil. In support, previous studies have demonstrated that PR application gained some positive impacts in acidic soils, but the efficacy was almost negligible in neutral and alkaline soils [21-22]. For instance, this was the case for maize grown in an acidic Lily soil (pH = 3.95) [23]. However, there are some discordant results showing that PR application was effective for rape (*Brassica napus* L.) when grown in an alkaline soil condition (pH = 7.72) [24]. Therefore, great efforts have been carried out to find the appropriate methods to enhance the solubility (efficiency) of indigenous RPs. For example, PR acidulation or the application of sulfur, OM or microorganisms (e.g., arbuscular mycorrhizal fungi and Pi-solubilizing bacteria) with PRs is among the most efficient techniques used for upgrading Pi availability [7,20,25].

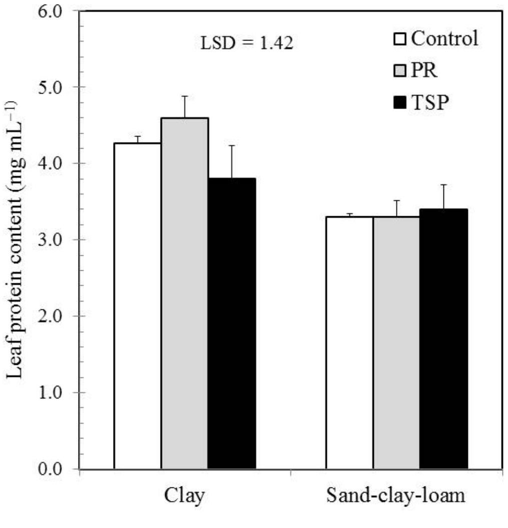

Fig. 3. Impacts of phosphate rock (PR) and triple superphosphate (TSP) on the leaf protein content for maize grown on clay or sand-clay-loam soil. Bars ± standard error of four replicates

Table 3. Impacts of phosphate rock (PR) and triple superphosphate (TSP) on the leaf chemical analyses for maize grown on clay or sand-clay-loam soil. Data presented are the means ± standard error of four replicates

Soil	Treatments	N	Pi	K	Ca	Mg
				(%)		
Clay	Control	0.68±0.02	0.16±0.04	0.48±0.02	0.21±0.02	0.09±0.01
	PR	0.73±0.04	0.17±0.01	0.56±0.03	0.20±0.03	0.12±0.01
	TSP	0.62±0.07	0.14±0.01	0.43±0.07	0.19±0.04	0.13±0.01
Sand-clay-loam	Control	0.54±0.01	0.13±0.02	0.46±0.05	0.23±0.02	0.10±0.02
	PR	0.52±0.03	0.14±0.03	0.41±0.02	0.24±0.05	0.08±0.01
	TSP	0.55±0.05	0.16±0.02	0.39±0.08	0.25±0.02	0.10±0.03
$LSD_{5\%}$		0.24	0.05	0.18	0.06	0.06

Table 4. Impacts of phosphate rock (PR) and triple superphosphate (TSP) on the rhizospheric chemical analyses for maize grown on clay or sand-clay-loam soil. Data presented are the means ± standard error of four replicates

Soil	Treatments	pH (paste)	EC_e (dS m^{-1})	N (%)	Pi (ppm)	K (meq L^{-1})	Ca (meq L^{-1})	Mg (meq L^{-1})
Clay	Control	7.9±0.03	1.3±0.21	0.05±0.01	0.7±0.08	0.96±0.23	3.6±0.4	1.13±0.26
	PR	7.8±0.02	1.5±0.04	0.05±0.01	0.5±0.10	1.04±0.22	4.0±0.3	0.98±0.20
	TSP	7.8±0.06	1.3±0.23	0.07±0.01	0.8±0.25	1.07±0.48	4.0±0.4	1.38±0.59
Sand-clay-loam	Control	7.7±0.02	0.6±0.02	0.06±0.00	0.5±0.08	0.84±0.06	3.8±0.4	1.25±0.23
	PR	7.7±0.06	0.5±0.03	0.06±0.01	0.7±0.12	1.12±0.49	3.6±0.3	0.91±0.06
	TSP	7.7±0.05	0.6±0.04	0.06±0.02	0.6±0.02	0.88±0.19	4.1±0.3	1.15±0.24
$LSD_{5\%}$		0.4	1.0	0.03	0.5	0.37	1.0	0.92

Beside the effect of soil pH, PR reactivity was also appeared closely connected to other factors related to soil and PR (minerology and chemical reactivity) material [26]. For instance, PR is less effective in soils with high Ca content, low OM, and/or a low CEC, due to the release of Ca ions during dissolution. Wilson and Ellis dissolved several different sources of PR in solutions with varying concentrations of Ca^{2+} and found an inverse relationship between the solubility of each PR and the concentration of Ca^{2+} in solution [27-28]. Low CEC may limit a soil's ability to sorb Ca^{2+}, especially if exchange sites are occupied by existing exchangeable Ca^{2+}, resulting in decreased dissolution [29]. On the other hand, the PR insignificant response might be partially related to the PR application rate (227.3 t ha^{-1}) used in this study. Increasing the rate of PR application was concomitantly followed by higher plant-Pi acquisition [30]. This could support the tendency that plant-Pi acquisition is effectively enhanced by soil PR enrichment [31].

3.2 TSP: As a Positive Control

The results of the positive controls (TSPs) were less or sometimes equal to most characterized PR treatments. When Pi fertilizers applied to calcareous soils and dissolved by soil solution, various reactions occur between Pi and soil constituents, thus, detach Pi from the solution phase and render it less variable i.e., Pi fixation/sorption [3,8,32]. This decreasing trend may be ascribed to the quick conversion of available Pi into insoluble complexes by entering into the immobile pools through precipitation reaction with highly reactive Ca^{2+} ions [6,33-34]. The extent of fixation and precipitation of Pi in soil is highly dependent upon the soil conditions such as pH, mineral content, soil moisture, clay content, calcareousness, and OM percentage of the soil [33,35-37]. Based on our and previous analyses, the two soils under investigation were alkaline (pH = 7.2–8.2), calcareous ($CaCO_3$ ~ 7.0–8.0%) and have Ca contents in the range of 2.0–2.5% [6,19]. In such types of soils, the concentration of plant available Pi is low, while the amount of insoluble Pi compounds is high [38-40].

In addition, the examined samples contained an average clay content of approximately 47.4% and 35.1% for clay and sand-clay-loam soil, respectively (Table 1). Numerous studies have indicated that soil clay minerals play a critical role in soil Pi fixation [e.g., 41]. Generally, clay minerals that possess greater anion-exchange capacities (due to positive surface charges) have a greater affinity for Pi ions [42]. The surface charge of clay minerals (and oxides) is partly pH-dependent, so that the anion-exchange capacity increases as pH decreases. Kaolinite is the dominant mineral particularly in the sand-clay-loam of El-Rawakeeb soil [19]. Although kaolinite has 10-20 cmolkg^{-1} CEC in El Rawakeeb soil [19], however, this 1:1 type of clays has a greater Pi retention capacity compared with 2:1 clay type [43]. Hence, soils containing large amounts of kaolinite clay minerals might retain larger quantities of externally applied Pi. Therefore, it is likely that kaolinite may be a dominant clay mineral that adsorbs high Pi [41]. As OM plays an important role in Pi solubilization through the acidifying and chelation mechanisms, the low level of OM in the soil may be also another determinant for the Pi trend in this study [44-45]. For instance, when an organic source of nutrition is applied, the bond of Pi compounds with lime ($CaCO_3$) is broken; thus, Pi is kept at higher amounts of availability [35].

4. CONCLUSION

The efficiency of Pi fertilizers is very low due to their fixation in alkaline soils that are predominating in the Sudan. The intensive usage of Pi fertilizers (i.e., TSP) as a very common strategy for sustaining plant Pi requirement, is not highly effective in calcareous and alkaline soils such as those used in the present study. Accordingly, it is indispensable to search for alternative nutritional management practices (chemical and biological) to improve plant growth, especially in alkaline low-fertile soils. The appropriate implementation of PRs can diligently contribute to sustainable agricultural intensification, especially in developing countries that has been privileged with vast PR resources (i.e., Sudan). However, the utilization of PR as a prime source of Pi fertilizer is suitable for acidic soils, while in calcareous soils, the high pH and $CaCO_3$ content decreases its solubility. Owing to the alkalinity nature of the two soils in question, the hypothesized beneficial effect of PR application on maize growth cannot be achieved. Hence, many efforts should be directed towards the efficient methods that can enhance the solubility of PR. Some suggestions might include: the partial acidulation of PR with H^+, combining the PR with WSPs, addition of sulfur, incorporation of OM residues/manures, and inoculation with arbuscular mycorrhizal fungi and Pi-solubilizing microorganisms.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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