Improving Grain Legume Yields in Gurué District, Mozambique Using Local Evate Rock Phosphate

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Improving Grain Legume Yields in Gurué District, Mozambique Using Local Evate Rock Phosphate

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ABSTRACT

Acid, infertile reddish-brown soils characterize large amounts of central Mozambique. Few of these soils are in food production representing a missed opportunity for agricultural productivity and a missed alternative to improve the food security of the country. These soils are mainly depleted of macronutrients such as N, P and K. Low levels of soil nutrients such as calcium, phosphorus, and potassium limit crop growth. Therefore, while N can be obtained from the air by biological nitrogen fixation (BNF) and organic sources, P and K as well others (Ca and Mg) must be provided from rocks and minerals. Local agricultural amendments for acid, infertile soils such as limestone and rock phosphate exist but are unexploited. An experiment was conducted to assess the feasibility of using local Evate rock phosphate (~ 40.7% total P_2O_5) as a corrective to supply phosphorus. The rock phosphate was applied at rates of ~ 20, 40, 80 and 160 kg total P ha^{-1}. For a comparison, triple super phosphate was also added at four P levels (~0, 10, 20 and 40 kg P ha^{-1}). A long growth cycle crop of pigeon pea (*Cajanus cajan* L., Mill sp. variety "ICAEP00020") with a growth cycle of 190 days was used to assess effectiveness of the local rock phosphate. A pigeon pea grain yield of 1000 kg grain

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ha^{-1} was possible with an application of 80 kg ha^{-1} of total P added as Evate rock phosphate. By comparison 20 kg P ha^{-1} as TSP was needed to reach a maximum yield of pigeon pea grain. This ratio suggests that Evate rock phosphate was 25% as effective as TSP on a total P basis. This research suggests that the Evate rock phosphate can be an effective amendment that can enable or enhance food grain production on the acid, infertile upland soils of Central Mozambique. Whether for direct application for acid-tolerant crops on acid soils or processed into soluble fertilizer phosphate, the existence of such a valuable resource provides a great opportunity for improved local food crop production.

Keywords: Rock phosphate; pigeon pea; acid soils; food grains; food security.

1. INTRODUCTION

In Sub-Saharan Africa (SSA), phosphorus has long been identified as the major limiting nutrient in the vast majorityof soils [1]. Such soils constitute up to 55% of the agricultural land in SSA [2]. SSA contains numerous rock phosphate deposits, and some are sufficiently reactive for direct application [3] and some are not. Direct application of indigenous rock phosphates has been viewed as an attractive option for building soil phosphorus (P) fertility because it potentially involves lower production costs andcapital investments than the production of water-solubleP fertilizers from indigenous rock phosphate sources [4,5]. In addition, phosphate rocks are more effective in tropical environments due the high temperatures and moisture regime which play a key role in rock dissolution, as well it represents inexpensive and environmentally sound fertilizer option for smallholder farmers with infertile soils and suitable climates [6-8].

Food security was the focus of agricultural projects including the Legume Innovation Laboratory, which has conducted farmer decision-making research regarding grain legume crops. A consistent limitation to food security has been the extremely low fertility and acidity of the highly weathered soils in the country (Maria and Yost, 2006). Recent studies indicate that such conditions are widespread in the central and northern, potentially highly productive regions of Mozambique. Soil management of nutrient poor acidic soils has been highly successful in other tropical regions with acid soils [9]. Multiple management alternatives are possible to convert these soils into productive ones.

The average rate of fertilizer use in sub-Saharan Africa (SSA) is 15 kg (nutrient-NPK) per ha compared to 269 kg/ha in Brazil (FAOSTAT Online Database (available at https://www.fao.org/faostat/en/#home, accessed November 2023.). The average fertilizer use in Mozambique is just 6 kg (nutrient)/ha. Thus it is not surprising that average yields of maize are among the lowest in Africa. The majority of soils in the SSA region are P deficient. Given the extremely low rate of nutrient use it is not surprising that crop productivity is also extremely low in SSA and, particularly so, in Mozambique. On the other hand, 26 countries in Africa have known/assessed PR deposits, and 22 in SSA including Mozambique [10].

In Mozambique, fertilizers such as superphosphates are exceedingly expensive, of low quality, and seldom available in local markets. Recent research has explored the possible use of indigenous agro-minerals such as rock phosphates, as substitutes for expensive, imported fertilizers. Rafael et al., [8] and [11], assessed the potential use of rock phosphate from Evate in acid soils by characterizing different size fractions and their rock phosphate reactivity as measured by an increase in crop yield. According to Zavale et al. [12], Mozambique can increase the production of nearly all crops by beginning to use some of its enormous potential in natural resources, improving agricultural infrastructure, increasing household adoption of improved crop varieties and adopting other new agricultural technologies.

1.1 Local Food Grain – Pigeon Pea

One of the crops of growing popularity among farmers in the acid soil region of Mozambique is pigeon pea (*Cajanus cajan*, L., Millsp.) (ICRISAT, Malawi). It is one of the most important cash crops for export mostly to India The crop is moderately tolerant of the acid soil conditions characteristic of the region and is well-known for drought resistance due to deep rooting. This crop is also tolerant of the acid soil conditions that are favorable for the reaction and dissolution of rock phosphates, and it has a long duration growth cycle, which is also favorable for slowly dissolving rock phosphates. The locally preferred cultivars of pigeon pea, for example, range in maturity from 170 to 190 days (O. Madzonga, ICRISAT/Malawi, personal communication, 2016; C. Malita (IIAM/Nampula), personal communication, 2016). Tolerance to soil acidity by pigeon pea is not well characterized, but several researchers have documented that the plant roots exude organic acids that dissolve and solubilize otherwise insoluble phosphates [13,14]. These researchers report that pigeon pea exudes some 10-fold more malonic acid than does groundnut, cowpea, or rice. Adugyamfi et al. [15] report that pigeon pea tolerates low P conditions better than soybean. For these reasons, *C. cajan* may be a useful rotation crop in food production systems in this zone of Mozambique.

1.2 Local Deposits of Rock Phosphate

Manhiça [16] characterized Mozambican phosphate deposits as primarily deposits of apatite of two types: (1) Monte Muande-Monte Fema in Tete Province, which was original crystalline limestones of Pre-Cambrian replaced and metasomatized together with injection of apatite-carbonate, apatite-magnetite, and apatite-silicate and (2) The Evate deposits in Nampula Province, which carbonatites with low contents of apatite dispersed or in hydrothermal veins. The Evate deposit was discovered during the geophysical investigations for graphite by a Russian team in 1983. The Evate deposit was initially quantified at 155,413,000 tons of apatite ore with an average content of 9.32% P_2O_5. [16,17]. Rafael et al. [8], in assessing the potential use of rock phosphate from Evate, concluded that this rock is suitable as a slow-release fertilizer in strongly acid soils and could lead to the replenishment of not only P, but also Ca and Mg.

The analytical methodology used by the Russian Team was unknown, however. In preparation for this research a sample of the Evate rock phosphate was submitted to the International Fertilizer Development Center (IFDC) Laboratory in Alabama, USA, and the results are given in Table 1.

Table 1. Analytical results of Evate rock phosphate sample (International Fertilizer Development Center, Muscle Shoals, Alabama. Analyzed November 9, 2015)

Chemical	Results	Analyst	Method
Total P_2O_5 (%)	40.7	CSG	$HNO_3/HClO_4$-Molybdovanadate color method - visible spec [18]
Citric Acid Sol. P_2O_5 (%)	3.75	CSG	SSSAP 1957 21 :183-188
Formic acid Sol. P_2O_5 (%)	2.12	CSG	ZPDB 1953 62:262-264
NAC Sol. P_2O_5 (% 1st ext.)	1.46	CSG	AOAC - Molybdovanadate color method - visible spec
NAC Sol. P_2O_5 (% 2nd ext.)	0.95	CSG	AOAC - Molybdovanadate color method - visible spec
Cd (ppm)	0.52	CSG	AFPC- HNO_3/HCL- ICP
Co (ppm)	7	CSG	AFPC- HNO_3/HCL- ICP
Cr (ppm)	9.8	CSG	AFPC- HNO_3/HCL- ICP
Cu (ppm)	14	CSG	AFPC- HNO_3/HCL- ICP
Mn (%)	0.1	CSG	AFPC- HNO_3/HCL- ICP
Mo (ppm)	2.2	CSG	AFPC- HNO_3/HCL- ICP
Ni (ppm)	4.7	CSG	AFPC- HNO_3/HCL- ICP
Pb (ppm)	14	CSG	AFPC- HNO_3/HCL- ICP
Zn (ppm)	22	CSG	AFPC- HNO_3/HCL- ICP

The objective of our study was to assess the potentialof using Evate rock phosphate of Mozambique to supply P for food grain legumes in the acid, infertile soils ofCentral Mozambique. Specifically, the study is aimed at determining the amount of locally available Evate rock phosphate in comparison with the imported, expensive triple super phosphate needed to achieve maximum yield and biomass of pigeon pea in a reddish-brown soil of the summit topographic position in Mepuagiua community of Gurué District, Zambézia Province, Mozambique.

2. MATERIALS AND METHODS

2.1 Study Area

Mozambique researchers have been using FAO, USDA Soil Taxonomy and other systems to classify and attribute names to soils that they worked on. In this study, the soils of the study area are named by its color due to lack of sufficient soil data for an accurate soil classification.

The experiment was conducted in Mepuagiua community, Gurué district of Mozambique. Gurué district is about 5,606 km² with a population of nearly 303,000. Gurué district is located at an elevation of 734 m and -15°27‟48.8 (south latitude), 36°58‟54.0 (east longitude). The district has wet/dry climate. Summer daily maxima temperatures range from 30 to 34°C. Winters have temperatures in the range of 17 and 20°C. Typical of tropical climates, winter is usually referred to as the dry season, while summer is called the rainy season. Average annual rainfall is 1900 mm. The climate in Gurué has much more rainfall than the rest of the province due to the orographic effect of the mountains thatsurround the town. The average maximum temperature is 24 to25°C and average rainfall per day is 57 to 165 mm (https://www.worldweatheronline.com/gurue-weather-averages/zambezia/mz.aspx).

2.2 Soils

Soils of the summit topographic position "Ehava" (Table 2) with the minimum values of soil properties (Table 3) were selected for the study. These soils are, according to local farmer knowledge, not capable of producing the important local food crops, including common bean (*Phaseolus vulgaris* L.).

Soils from six sites in the Mepuagiua community were analyzed and selected chemical and physical properties are summarized in Table 3. The reddish-brown soils are located in the summit topographic position and are characterized by the minimum values in all soil properties (Table 3) and low pH, low soil Ca and Mg that suggest a highly weathered soil. The low levels of cations, especially the low Ca^{2+} and Mg^{2+} and low effective cation exchange capacity (ECEC), confirms the low activity of the clays and the status as being highly weathered and indicating a very low capacity of the soils to retain nutrient cations, a condition typical of highly weathered soils of the tropics. There is a wide range in soil C contents, but generally it is very low as well such that soil C may not be contributing to soil nutrient content nor retention capacity. The variation in soil texture observed in field is reflected in the range of both soil sand and clay contents.

Soils from the experimental site (Table 4) represent the acid, more highly weathered range of soils reported in Table 3.

2.3 Chemical Analysis Methods for Phosphate Rock

Table 1 provides the analytical results of the Evate rock phosphate according to reference methodology of the International Fertilizer Development Center, a worldwide authority and reference on rock phosphate deposits and characteristics.

Table 2. Local soil names, characteristics, Indicator crop, catena location, and farmer reported predominant crops in Mepuagiua

Soil types	Characteristics	Indicator crop	Catena location	Predominant crops
Ehava	Sandy reddish- brownish	Pineapple, pigeon pea	Summit	Cassava, pineapple, sorghum, and fava beans
Ekotchokwa	Reddish soil	Pineapple, pigeon pea	Backslope	Cassava, sorghum, pineapple, and fava beans
Epupu	Blackish soil, less moisture, less clay content	Amaranthus, pigeon pea	Footslope	Maize, common bean, pigeon pea butter peans, amaranthus
N‟tchokwa	Blackish, high moisture, high level of clay particles	Elephant grass (?)	Toe slope (river streams)	Rice, beans, maize and sugar cane

Table 3. Selected chemical and physical properties of soil of Mepuagiua community, Gurué district, Mozambique

Depth	pH	Soil C	Ca2+	Mg2+	K+	Sand	Silt	Clay	ECEC	ECEC/clay
Cm		g kg^{-1}		cmolc kg^{-1}			%		cmolc kg^{-1}	cmolc kg^{-1} $\%^{-1}$
0-15	4.9-6.5	10.0-37.0	1.8-17.6	0.85-2.6	0.09-0.62	33-63	7.3-30.5	23.4-45.4	3.44-8.57	7.58-35.5
15-30	5.3-6.3	7.5-33.7	3.1-10.3	1.1-2.0	0.11-0.50	37-61	5.3-24.5	34.4-45.4	5.04-12.9	10.1-50.8

Soil pH was obtained from a 1:1 soil: water ratio, Cations Ca, Mg, were measured in a neutral salt extraction (1 M KCl). Potassium was measured in a sodium bicarbonate extractant used for phosphorus. Effective CEC was obtained by summing the cations plus the KCl-extractable acidity

Table 4. Selected soil chemical properties of experimental plots, Mepuagiua community, Gurué district, Mozambique. Depth 0-15 cm

Parameter	pH	Bicarbonate P	Ca^{2+}	Mg^{2+}	K^{+}	KCl-extractable acidity (largely Al^{3+}
		mg kg^{-1}			cmolc kg^{-1}	
Median	5.03	15	0.62	0.53	0.40	0.40
Range	4.56 - 5.66	10 - 47	0.35 - 1.93	0.27 - 1.5	0.04 - 0.85	0.04 - 0.85

Because phosphate rock serves as a vital raw material in the production of fertilizers, it plays a pivotal role in enhancing soil fertility and supporting agricultural productivity. The chemical composition of phosphate rocks significantly influences their efficacy as a source of plant-available phosphorus. In this section, we describe the chemical analysis methods used to characterize the Evate rock phosphate sample, employing various methodologies recommended by the International Fertilizer Development Center (IFDC) to assess its suitability for agricultural and industrial applications.

2.3.1 Analysis

2.3.1.1 Total P_2O_5 analysis

The first step in understanding the potential of Evate rock phosphate involves determining its total phosphorus content. Following the procedure outlined by the Association of Official Analytical Chemists (AOAC) in [19], one gram of the sample undergoes acid digestion using strong acids on a hot plate. The phosphorus concentration in the resulting filtrate is then measured using a spectrophotometer based on UV-Vis, where orthophosphate forms a highly colored yellow molybdovanadate-phosphate complex.

2.3.1.2 Neutral ammonium citrate (NAC) extraction

Another crucial aspect of the chemical analysis involves assessing the solubility of phosphorus in the rock. The neutral ammonium citrate extraction method, also following the AOAC guidelines from 1970, involves subjecting a gram of the sample to extraction with 100 ml of neutral ammonium citrate solution at 65°C for an hour. The phosphorus concentration in the filtrate is subsequently determined using UV-Vis spectrophotometry. The NAC second (NAC2) method extracts the residual PR sample after the first extraction (NAC1) to eliminate the possible effect of free carbonates (calcite and dolomite) on apatite solubility in NAC [20,21].

2.3.1.3 Extraction with 2% citric acid

The third method involves extraction with 2% citric acid, as per AOAC standards from 1960. This process, performed at room temperature for one hour, enables the assessment of phosphorus forms that are soluble in citric acid, providing insights into the potential plant availability of phosphorus in the rock.

2.3.1.4 2% Formic acid extraction

The fourth extraction method, using 2% formic acid, is based on the procedure outlined by Hoffman and Mager in [22]. This extraction, also conducted at room temperature for one hour, contributes to understanding the range of phosphorus forms that can be released from the rock under specific conditions.

2.3.1.5 Acid ammonium citrate (pH 3) extraction

The fifth extraction method, utilizing acid ammonium citrate (pH 3), follows an unpublished IFDC-TVA procedure. This extraction, performed at room temperature for one hour, helps evaluate the potential phosphorus forms released under mildly acidic conditions.

2.3.1.6 Multi-element analysis (Cd, Co, Cr, Cu, Mn, Mo, Ni, Pb, Zn)

In addition to phosphorus, the presence of other elements like Cd, Co, Cr, Cu, Mn, Mo, Ni, Pb, and Zn is assessed using methods adopted by the Association of Fertilizer and Phosphate Chemists. A half-gram of the sample undergoes digestion with a nitric hydrochloric mixture on a hot plate, and the resulting solution is analyzed using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES).

The information obtained from these analyses serves dual purposes. Firstly, it aids in understanding the reactivity of Evate rock phosphate, simulating conditions it might encounter in soil environments. Secondly, it provides insights into the potential impact of the rock on the environment and its suitability for agricultural use.

The choice of extracting agents, including neutral ammonium citrate, citric acid, formic acid, and acid ammonium citrate, allows for a comprehensive understanding of the range of phosphorus forms that can be made available to plants. Additionally, the multi-element analysis sheds light on the concentrations of elements critical for evaluating environmental and agricultural implications.

2.4 On-Farm Experiment

An on-farm experiment was established to compare the availability of P supplied by Evate rock phosphate with that of the expensive, imported triple super phosphate (TSP). The experiment was a randomized complete block design with 3 replicates and 8 treatments per replication. An experimental plot consisted of 6 rows:6 m long and 3 m wide. Furrows were opened for each line of 6 m long per plot using a hoe. Seeds were planted 0.5 m between each row and 0.4 m within the row. Seeds were placed on the left side of the furrow and fertilizer on the right side and then covered with soil. The Evate phosphate rock for the experiment was crushed and ground so that 90% passed the 0.005mm (100 mesh) sieve and 30% also passed the finer sieve of 0.002mm (200 mesh). The Evate rock phosphate was applied at 20, 40, 80 and 160 kg total P ha^{-1} and the TSP was applied at 10, 20 and 40 kg total P ha^{-1} Twenty kilogram of N was applied per hectare as a starter for the legume crop, in the form of urea and 40 kg of K_2O ha^{-1} was applied as potassium chloride as blanket applications of these nutrients for all treatments. Planting took place on 20 January 2016 and the first weeding was done on 5 February 2016. Harvest took place 27 August, 2016 after 220 days of growth.

2.5 Crop Selection

The pigeon pea variety selected for the first crop in this rotation experiment (ICAEP00020) has a relatively long growth cycle of 190 days. Local farmers in Central Mozambique and Malawi are accustomed to using varieties of even longer growth cycles of 240to 270 days (Dr. O. Madzonga, ICRISAT/Malawi, personal communication 2016). ICRISAT/Malawi has introduced varieties of medium duration (160 to 190 days) in the Gurue district, but adoption seems slow. Local practice is to seed at very low plant populations such as 1 m apart (Malawi recommendations are to space hills at 90 cm × 90 cm). For this experiment a much closer spacing of rows 50 cm apart with hills placed at 40 cm apart in the row was chosen. This plant population still seems too low to obtain maximum grain yield.

2.6 Data Collection

2.6.1 Crop measurements

Non-destructive and destructive measurements of six selected plants were taken and recorded at approximately two week intervals throughout the growth cycle. These measurements included plant height, stem circumference and plant population. At harvest pigeon pea pods were collected from the four central rows, which comprised a harvest area of 12 m^2. Pods were weighed and air-dried for final weight and yield calculation. Above-ground biomass was also collected, weighted, and sub-samples taken for dry weight calculation.

2.6.2 Soil measurements

Soil samples were taken from each experimental plot after harvest to assess suspected gradients of soil pH. Samples of each plot were composites of 3 sub-samples taken from the plot harvest area. Soils were analyzed for soil water pH (1:1 ratio), 0.5 M sodium bicarbonate, soil calcium, magnesium and KCl-extractable aluminum determinations were also made. Effective cation exchange capacity was calculated by summing the cations Ca^{2+}, Mg^{2+}, K^+ and KCl-extractable Al. The initial survey samples from six sites are listed in Table 3, while data from the experimental site are listed in Table 4.

2.7 Statistical Analysis

A randomized complete block ANOVA was calculated on yields and above ground biomass yields using both Statistix® v. 10 statistical analysis software and JMP [23]. The results were plotted using Sigmaplot® v. 12.5 graphics software. Plots of the relationship between grain, biomass, plant height and stem circumference and total amounts of applied P either in soluble TSP form or in the form of rock phosphate were developed. These plots served to quantitatively compare pigeon pea response to the Evate rock phosphate in relation to that of TSP and permitted a comparison of relative solubility and availability of the P in the Evate phosphate.

Because substantial variation in soil pH was observed among the experimental plots (Table 4), contour plots of soil pH, grain and biomass yields were prepared using the Surfer® version 12.8 software. Individual plot yields and corresponding mean soil measurements for the plot provided the basis for the contours. Other plots of yields in relation to soil measurements were developed to explore the effect of soil acidity on pigeon pea growth and response.

3. RESULTS AND DISCUSSION

Pigeon pea yielded as much as 1200 kg grain ha^{-1} (Fig. 1). These yields were similar to or greater than average pigeon pea grain yields of the Gurué District (2014) of about 800 to 1000 kg ha^{-1}(ICRISAT/Malawi, Dr. O. Madzonga, personal communication 2016). Yields were high even with no soluble TSP fertilizer. The results suggest that a level of 15 mg kg^{-1} was sufficient Grain yields where the local rock phosphate was applied were higher than expected with yields reaching almost 1200 kg ha^{-1}. A closer comparison shows that maximum yields occurred withTSP rates of 20 kg P ha^{-1}. for pigeon pea. Rock phosphate has low reactivity compared with water soluble P fertilizer such as TSP. X-ray diffraction analysis revealed that the Evate rock phosphate was mainly made of fluoroapatite. Calcium and P, followed by Si, Al, Fe, K, Sr, and Ba were the major constituent elements of the rock phosphate. The total P content in rock phosphate satisfies the European legislation for direct application with threshold of 250 g kg-1. The fluoroapatite dissolution is higher in strongly acid environments. Alternatives to increase fluoroapatite reactivity include grinding rock materials because the dissolution rate of rock-forming minerals increases as the specific surface area increases, which occurs with a decrease in particle size. This was evidenced during the dissolution experiment with Evate rock phosphate whereas the release kinetics were determined for both P and Ca, which are important nutrients in the rock phosphate fractions. The fine fraction resulted a higher dissolution rate than the other particle-size fractions [8].

Pigeon pea yields where rock phosphate was applied were surprisingly high given the low solubility of the material (3.75%) and were almost similar to yields where the soluble TSP fertilizer was applied. This relatively high effectiveness of Evate rock phosphate may be related to several factors that may have led to the relatively high availability of the Evate rock phosphate:

1. The pigeon pea growth cycle is long and in this case the crop was harvested after 220 days of growth allowing a long time for rock phosphate dissolution.
2. Pigeon pea is known for the exudation of large amounts of the low molecular weight organic acids, malonic acid that solubilizes otherwise unavailable forms of soil phosphorus [13].
3. Soils of the experimental site are both acidic (ranging in soil pH from 4.5 to 5.7) and low in exchangeable bases such as Ca (ranging from 0.4 to 2 $cmol_c$ kg^{-1}), which are well known factors that enhance rock phosphate dissolution [24,13].
4. The rock phosphate was crushed and ground such that 90% was finer than 0.005mm and 25-30% was finer than 0.002 mm.

This result indicates that in these conditions, Evate rock phosphate was an effective source of P.

Field observations of pigeon pea growth during the experiment revealed zones of superior growth and plant height unrelated to treatment. In addition, grain yields on the control treatment (no P added) plot were surprisingly high (Fig. 2) leading to inquiry into the experimental plot preparation. A comparison of soil measurements from individual plots indicated a large variation in soil pH as well as in levels of calcium, magnesium, and other nutrients (Fig. 3). This analysis revealed that two of the three replications of the control plot were on plots with abnormally high soil pH. These differences were not apparent when soil was sampled by compositing by blocks, replicates, or across the entire site. In addition, variation in three variables, soil pH, soil Ca^{2+} and soil Mg^{2+} seem closely related. This variation appears to have resulted from the preparation of the experiment whereby all plant residue from the experimental area was gathered and burned in the plot center, clearly a time efficient alternative, but not optimal for the experimental objectives. A further analysis suggests that, in fact, the pigeon pea did respond to the gradient on soil pH induced by burning of plant residue from clearing (Fig. 4). These results do suggest that while pigeon pea is known for its tolerance to soil acidity, it did respond to the reduction in soil acidity and less toxic extractable Al as well as increased levels of Ca^{2+} and Mg^{2+}.

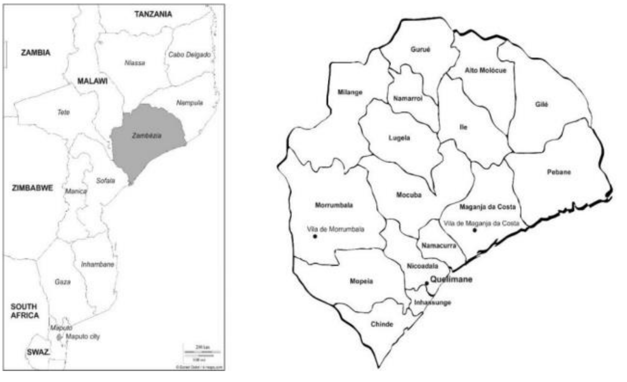

Fig. 1. Location of the Gurué District, Zambézia Province, Mozambique

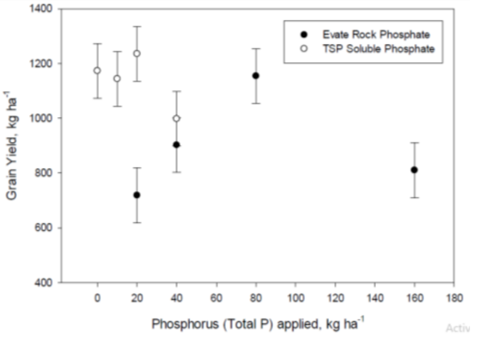

Fig. 2. Grain yields of pigeon pea (*Cajanus cajan*) as influenced by rate and source of phosphate. The bars represent standard errors of treatment means

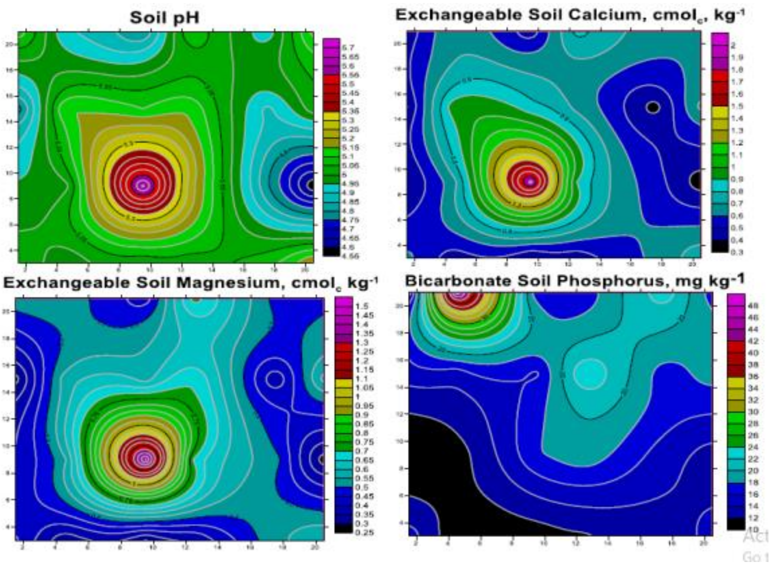

Fig. 3. Variation in soil pH, exchangeable Ca^{2+}, Mg^{2+}, and P after pigeon pea harvest

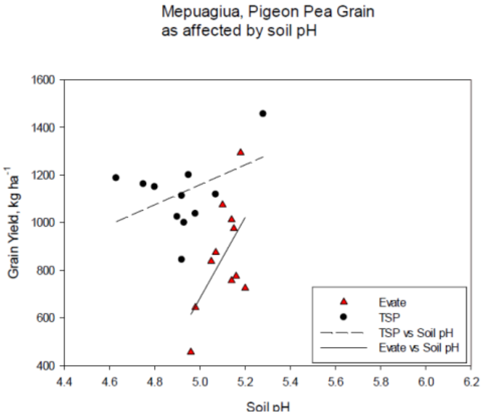

Fig. 4. Relationship between grain yield and soil pH of all treatments

Soil measurements on a per plot basis (Table 4) indicate an unfortunately wide range in pH, Ca, and Mg as mentioned previously. The levels of soil pH are clearly in the acidic range and suggest that acid tolerant plants such as pigeon pea, cassava, cowpea, and certain varieties of peanut would likely be most successful on such soils. The levels of soil P were variable, but generally low relative to typical plant requirements. Levels of soil Ca and Mg were particularly low indicating very low cation retention capacity of the soils. With such low levels sufficiency of Ca might be limiting for certain legumes [9].

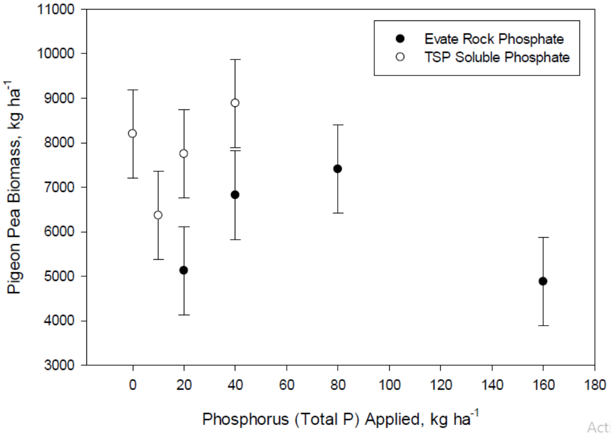

Fig. 5. Pigeon pea above ground biomass in relation to source and amount of applied P

An analysis of pigeon pea aboveground biomass inrelation to source and rate of applied phosphate revealed essentially the same pattern of response as did grain yield results (Fig. 5). The biomass results also indicates that the Evate rock phosphate effectively supplied nutrients to this pigeon pea crop and in this acid, infertile soil.

4. CONCLUSIONS

A pigeon pea grain yield of 1000 kg grain ha^{-1} was obtained with an application of 80 kg ha^{-1} of total P addedas Evate rock phosphate. By comparison 20 kg P ha^{-1} as TSP was needed to reach a maximum yield of pigeon pea grain. If this relationship was used to estimate relative effectiveness it is 20/80 or 25%. This research suggests that the Evate rock phosphate can be an effective amendment and slow-release fertilizer that can provide available P and enable food grain production on the acid, infertile upland soils of Central Mozambique.

Evate rock phosphate, in this combination of soils and crops was an effective source of the often missing nutrient P for food grain production in Mozambique. This rock phosphate has an unusually high level of P (40.7% P_2O_5), however solubility is low (3.5 citric acid solubility and 0.95 neutral ammonium acetate solubility). These values are high in total P and low in solubility compared with data from Smallberger et al. [25]. The solubility of this rock phosphate can be improved by increased surface area with the especially fine grinding applied in this experiment, used on acid soils, and by enhancing with other P sources and with crops of either long duration and / or that acidify their rhizosphere. Some researchers report that acidulation of the PR with different chemicals and acids can increase the reactivity of the PR [26,27].

Use of this potentially very important local fertilizer resource needs to be tested in other conditions and cropping systems, as well as with different particle size fractions whereby the dissolution might be initiated and largely carried out during the pigeon pea cropping period. Other research shows that subsequent crops also benefit from the residual P released during the pigeon pea phase of the rotation, which needs to be tested. Additional field experimentation using this rock phosphate is needed to quantify and assess its potential role in increased food crop productivity in Central Mozambique.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Biography of author(s)

António Rocha
Agri-Food Department, SNV Netherlands Development Organization, Avenida Tomás Nduda, N° 1214, Bairro da Polana Cimento, Maputo, Mozambique.

My agricultural journey commenced in the early 2000s before enrolling at Mozambique Catholic University in Cuamba district, Niassa province, Mozambique. Introduced by my parents to agronomists, I grasped the vital role of agriculture, echoing former President Samora Machel's words, ***"Agricultura é a base de desenvolvimento de um país"*** (Agriculture is the basis of a country's development).

Engaging in field experiments during my training in the Cuamba district, I witnessed communities reliant on agriculture for subsistence. This experience fueled my commitment to support farmers in overcoming obstacles and reducing poverty.

From 2006 to 2008, I worked with Vanduzi Company in Chimoio, gaining practical experience. Subsequently, I collaborated on projects with the International Fertilizer Development Center (IFDC) from 2008 to 2013, honing skills in assisting smallholder farmers in the central region.

Between 2013 and 2014, I focused on cassava, maize, pigeon pea, and soybean farming in the Beira and Nacala corridors, collaborating with CIMMYT and DADTCO (Dutch Company). Pursuing further education, I obtained an MSc in Soil Science from the University of Hawai'i from 2015 to 2017, focusing on reducing food insecurity and providing production alternatives to farmers.

From 2018 to 2022, I contributed to the MozRice Project AFAP (African fertilizer and agribusiness partnership) in Zambezia province, training rice producers and enhancing the Agrodealers network. Subsequently, from 2022 to 2024, I joined SNV (International Netherland Organization) in the Northern Province, training internally displaced people to cultivate fresh vegetables and connecting them with mining companies as potential buyers.

Ricardo Maria
Instituto de Investigações Agronómica de Moçambique, Mozambique.

He was born in 1971 in Zambezia province, central Mozambique. He completed his primary and secondary schools in Quelimane, the capital of Zambezia province. He holds a BSc from Eduardo Mondlane University, Department of Rural Engineering. After completing his BSc, he worked at the Institute of Agricultural Research of Mozambique (IIAM), Department of Agronomy and Farming Systems. During this period, he was the country representative of Farming System Research, a regional professional organization. He completed his Master's degree in Tropical Plant and Soil Sciences from the University of

Hawai'i at Manoa in 2004. After completing his Master's Degree, he became an assistant director for the central soil and plant tissue testing laboratory and coordinator of soil health research activities led by IIAM. In 2010, he pursued his PhD degree at the University of Nebraska, Lincoln at the Department of Agronomy and Horticulture and completed course work. Currently, he works for the Institute of Agriculture Research of Mozambique, Department of Agronomy and Natural Resources. He is coordinating the RESADE project funded by the International Fund for Agricultural Development (IFAD) through the International Center for Biosaline Agriculture (ICBA).

Rogério Rafael
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He is an Assistant Professor at Universidade Eduardo Mondlane, Faculty of Agronomy and Forestry Engineering, Head of Rural Engineering Department, Soil Science Division. He is a researcher and consultant in Agriculture, Soil, and Environment based in Maputo. He has done several works in the Agricultural sector for both the Mozambique Ministry of Agriculture, as well as NGOs and Private Sector. He has taught soil science and fertility to graduate and Post-graduate students at Eduardo Mondlane University. He also has mentored many colleagues and students (BSc, MSc and PhD). He has at least 7 research articles in peer-reviewed journals and more than 6 working papers. Recently, he has been involved in the following works:

- Project manager for a project Improving soil health, food security, and livelihood of smallholder farmers in Mozambique through the development and use of appropriate fertilizer blends
- Coordination of project Sustainable improvement of the fertility of acid soils from Mozambique: application of phosphate rock, limestone, and biochar
- Coordination of a project for strengthening the vegetable value chain of smallholder farmers in Maputo province (Boane and Namaacha districts) with the main role of managing all aspects of the project proposal development and implementation to ensure on-time performance and positive impacts
- Increasing water productivity. for nutrition-sensitive agriculture for improved food security and nutrition
- Monitoring land and water productivity by Remote Sensing
- Diagnosis of Acidity – Quality of Amendments – Recommendation of Application (DaQaRa)
- Analyzing the impact of SUSTENTA´s Agriculture Extension approach on beneficiary farmers in Inhambane and Sofala provinces
- Enhancing Drought Early Warning in Mozambique through Satellite Soil Moisture Data to support food security in the context of climate change.

With a strong background in Agriculture, Environment, and Natural resources, he has strong skills in data analysis (using Excel and R program), Laboratory management and analysis, monitoring and evaluation of development projects, field surveys, and coordination of agricultural projects, mainly in environment and agriculture-related areas.

Job Fugice
International Fertilizer Development Center, Muscle Shoals, Alabama, USA.

He is a Brazilian-born. He has devoted his career to the intricate relationship between soil and agriculture. His academic and athletic journey began at the University of North Alabama, culminating in a Bachelor's degree in Chemistry and Biology, followed by an MBA in 2010. Driven by a passion for advancing agricultural practices, he pursued a Master's in Agriculture with a focus on Soil Chemistry at Auburn University in 2021.

With a rich 17-year career at the International Center for Soil Fertility and Agricultural Development (IFDC), his trajectory has been characterized by innovation and leadership. Starting as a Chemical Analyst and currently as a research Scientist Manager, he delved into R&D and transformative projects for global food security. His commitment to circular economy principles is evident in his work on innovative fertilizers to mitigate greenhouse gases.

Beyond IFDC, he actively contributes to international committees on fertilizer methodologies, impacting standards like AFFPCO, ISO, and IFA. With fluency in Portuguese, English, and Spanish, he leverages linguistic skills for global collaboration.

Upendra Singh (Vice President Research and Chief Scientist)
International Fertilizer Development Center, Muscle Shoals, Alabama, USA.

He is a soil scientist/systems modeler. He has more than 35 years of experience in soil-plant-nutrient dynamics and fertilizer research with an emphasis on the development/application of crop simulation models and decision support systems in agricultural research, extension, and decision-making. He coordinates and conducts research in collaboration with National and International Agricultural Research Centers on better understanding and quantification of nutrient dynamics and environmental processes; development/co-development and evaluation of new fertilizer formulations; and development, field testing, and application of decision support software to simulate biophysical processes, with special emphasis on sustainable agriculture, crop yield forecasting, nutrient dynamics, and environmental quality. He has conducted research projects and training programs in over 36 countries and has more than 200 publications. His key contributions have been in the development of the nutrient dynamics module for the Decision Support System for Agro technology Transfer (DSSAT) and the Phosphate Rock Decision Support System (PRDSS).

Ms. Unasse Saide Uaite
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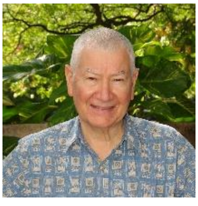
She completed her graduation from Universidade de Cuamba. She began working as a field technician with the Legume Innovation Program of the University of Hawai'i, a joint Mozambique/Uganda technical assistance program. The program was carried out in Gurue, Zambezia Province, Mozambique with the Institute Media Agro-Industrial of Gurue (IMAIG). She was the key field technician for the study on Evate rock phosphate in this chapter. She learned how to collect sample soils, take GPS measurements, and carry out simple laboratory measures of soil properties. She learned that the soil of the summit position in Mepuagiua was extremely acidic such that the key food crop of the community and district. Beans (*Phaseolus vulgaris)* could not be grown there without the application of limestone. After the conclusion of the project on evaluating Evate rock phosphate, she was hired by IMAIG to continue as a Professor where she taught many courses for around 400 students and began a food-gardening program for the Institute. In 2020, she traveled to Maputo for training under the Ministry of Agriculture and Rural Development where she developed business plans and learned about workplace health and safety, Forestry, laws, and specific challenges for Mozambique.

Kim Falinski
Nature Conservancy, Hawai'i, USA.

She leads strategic planning around land-based pollution that connects to the ocean for the Hawaii and Palmyra Chapter of The Nature Conservancy. As an environmental engineer and soil scientist by training, she works to make the case for projects that can reduce wastewater and sedimentation impacts on nearshore ecosystems. When possible, she works to include nature-based and indigenous-knowledge solutions into her work, including considering the role of wetlands, taro fields and bioswales in capturing nutrients and soils. She has been a technical advisor for a Maui-based community water quality program since 2015 and helped to use that data to advocate for watershed management actions. Most recently, she has been involved in coordinating the environmental response and planning by community, academia and government to the Lāhaina wildfires. She holds a PhD from the University of Hawaii at Mānoa in Tropical Plant and Soil Science (mapping sediment transport across the archipelago), an MSc from Cornell in Biological and Environmental Engineering and a BS in Electrical Engineering from MIT. She is a Professional Engineer for the state of Hawaii.



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He is Professor Emeritus at the University of Hawai'i at Mānoa, the US. He has carried out international research programs in West Africa, Angola, and Mozambique. His dissertation took place in Brazil and he maintains close ties there. He also taught and carried out research while at the University of Hawai'i and multiple international research programs in Africa, S. America, SE Asia, Indonesia, Thailand, the People's Republic of Laos, and the People's Republic of China. His areas of interest include soils and crops of the tropics, legumes, spatial analysis, and especially geostatistics. He has sought to apply these skills to improve food security and mitigate the effects of climate change while improving the health and resilience of the environment. He supervised some 43 graduate students while carrying out both domestic and international active graduate programs.

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