THE EFFECT OF TIMES OF CONTACT AND RATES OF MINJINGU PHOSPHATE ROCK (MPR) ON ITS DISSOLUTION IN AN OXIC (KANHAPLIC) HAPLUSTULTS

BY

JUSTUS VINCENT NSENGA

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ABSTRACT

An incubation glasshouse pot experiment was conducted at the Sokoine University of Agriculture Morogoro, Tanzania to study the effect of time of contact and rates of Minjingu phosphate rock (MPR) applied to an Oxic (Kanhaplic) Haplustults on its dissolution and the release of P and Ca for plant uptake. The soil was mixed with MPR at rates equivalent to 0, 50, 75, 100 and 150 kg P/ha. The incubation periods were 120, 90, 60, 30 and zero days prior to sowing the maize (*Zea mays*. L. var. Staha). The moisture content in the soil was maintained at about field capacity during the incubation period and throughout the maize growing period with distilled water. Results from this study showed that MPR dissolution increased significantly with increase in MPR rates and incubation period. However, the increase in the amounts of P released tended to increase with time of incubation up to about 75 days and decreased thereafter. Presumably the P released was largely sorbed by Al and Fe oxides in the soil. The amounts of MPR dissolved ranged from 1.17 to 13.11 mg P/kg and 10.74 to 15.91% as regards to extractable P and ΔP% values, respectively. The interaction between equilibration periods and MPR rates explained about 86.8% of the variation in MPR dissolution, MPR rates predicted about 76.6% of the dissolution of MPR, and 10.3% of the dissolution predicted by equilibration period. The soil pH and extractable Ca were found to increase slightly with increase in MPR rates but decreased with increase in incubation period. The exchangeable acidity and exchangeable Al decreased with increase in MPR rates, and slightly increased with increase in incubation periods. Maize dry matter yields, P and Ca uptakes were found to increase significantly with increase in

MPR levels. Elemental P and Ca contents in the plant materials were found to decrease significantly with the increase in MPR rates probably indicating the effect of dry matter yield on nutrient dilution or depletion of phosphate and Ca^{2+} in the soil. Application of MPR at sowing time led into higher dry matter yields than when applied prior to sowing and increase in incubation period decreased the uptakes of P and Ca though inconsistent with %P and %Ca in the plant shoots. Application of MPR at sowing time was recommended for Oxic Haplustults which are strongly acid, with low amounts of P and exchangeable Ca in order to increase the agronomic effectiveness of MPR.

DECLARATION

I, JUSTUS VINCENT NSENGA, do hereby declare to the SENATE of Sokoine University of Agriculture that this dissertation is the result of my original work and has not been submitted for a degree award in any other university.

Signature ....

Date 20|02|2001

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DEDICATION

This work is dedicated to my beloved mother, the late Anna A. Nsenga, my aunts Christina A. Nsenga and Asia A. Nsenga who cordially decided to take me to school. In memorial of the late grand mother Tausi M. Wa-Nsenga who kindly provided with me a good mothery care during her life.

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LIST OF ABBREVIATIONS AND SYMBOLS

SFI	Soil Fertility Initiative
PR	Phosphate Rock
MPR	Minjingu Phosphate Rock
GDP	Gross Domestic Product
FAO	Food and Agriculture Organization
GPR	Gafsa Phosphate Rock
NCPR	North Carolina Phosphate Rock
SUA	Sokoine University of Agriculture
Al	aluminium
Fe	iron
P	phosphorus
Ca	calcium
$PO^{3-}{}_4$	phosphate ion
$CO^{2-}{}_3$	carbonate ion
pH	negative logarithm of hydrogen ion concentration
CEC	cation exchange capacity
H^+	hydrogen ion
$NaHCO_3$	sodium hydrogen carbonate
CO_2	carbon dioxide gas
HF	hydrogen fluoride
N	nitrogen

$CaCl_2$	calcium chloride
K^+	potassium
Mg^{2+}	magnesium
Na^+	sodium
NH_4NO_3	ammonium nitrate
NH_4F	ammonium fluoride
NH_4Ac	ammonium acetate
%	percent
<	less than
>	greater than
*	significant
Δ	delta (change)
ppm	parts per million
µm	micromitre
µg	microgram
mg/kg	miligram per kilogram
ha	hectare
TSP	triple superphosphate
SSP	single superphosphate

CHAPTER ONE

INTRODUCTION

In Tanzania, the agricultural sector has been playing a great role to her economy as it employs about 84% of the total population, for the production of food for domestic consumption and export as well as industrial raw materials (Tanzania Soil Fertility Initiative; SFI, 1999). Moreover, this agricultural sector accounts for about 60% of the Gross Domestic Product (GDP) of which the dominant sub-sector is food production which accounts for about 55% of the agricultural GDP. However, apart from many other problems facing the agricultural sector like prevalence of crop plant pests, unreliable rains and markets for the agricultural products and the like, the deterioration of soil fertility in Tanzania poses a potential threat to her agricultural sector and the national economy as a whole.

It has been argued that, the development of appropriate technologies to maintain and improve soil fertility is paramount in order to produce large amounts of food and fibre for the world's population (Brown *et al.*, 1994). This is particularly so in tropical African countries which have been quoted as the ones with the highest population growth rates or with a high absolute increase in the number of people and yet soils tend to be more highly weathered and of low inherent fertility, hence low crop production (Sanchez, 1976; FAO, 2000). According to the Tanzania Soil Fertility Initiative (2000), the human population in Tanzania is currently estimated to be about 29 million people and is expected to reach 84 million by the year 2025, whereby 17 out of the 20 regions would become food deficient if soil productivity is not improved.

The low level of available phosphorus (P) in the majority of the agricultural soils is considered to be as one of the serious fertility constrains in tropical soils, Tanzanian soils inclusive (Sale and Mokwunye, 1993). This problem of low plant available phosphorus is due to the low P-contents in the soils' parent materials and the high capacity of other soils to immobilise P. For example, phosphate inherently found in soil and that added to the soil in the form of inorganic fertilisers, manures and crop residues react with iron (Fe) and aluminium (Al) to form Al phosphate/Fe phosphate compounds which are insoluble thus do not contribute much to plant nutrition. Soil fertility decline has also been brought about by successive and continuous cropping without proper fertiliser and soil management practices.

Adequate P fertilisation has, therefore, been recommended as one of the essentials for economic and sustained crop production in such highly weathered soils (Menon *et al.*, 1991; Sanchez, 1997). However, the use of water soluble P fertilisers (conventional P fertilisers) like triple superphosphate (TSP), single superphosphate (SSP), NPK, and diammonium phosphate (DAP) and other soluble P fertilizers in Tanzania has decreased from about 99,000 tonnes in 1993/95 to about 65,000 tonnes in 1996/97 season which is almost half the amount used in the early 1990s (Turuka and Ulotu, 2000). This decline in P fertiliser use is a consequence of the deterioration of crop products' prices over the years and the increase of water soluble P fertiliser prices in the world market (Kimbi, 1991; Ponte, 1999). As a consequence, these P fertilisers have been out of reach of the smallholder farmers who dominate the agricultural production sector in Tanzania.

A search for effective and cheaper alternative P sources is, therefore, of great necessity if production is to be sustained. Farmers should, therefore, be encouraged to use naturally occurring materials which are considerably cheaper like farmyard manure, composts and phosphate rock that can supply the basic plant nutrients. However, based on the reactivity and dissolution of PRs, these PRs have been found to be more suitable for direct application to ameliorate P deficiencies in acid soils (Engelstad and Terman, 1980; Semoka *et al.*, 1992). Engelstad and Terman (1980), documented further that no PR source would be effective in soils having pH levels > 6.0. Since the majority of the tropical soils, Tanzania inclusive, are highly weathered with acid reactions, then undoubtedly, PR would be the cheapest and appropriate P-source for crop production. Additionally, as an advantage of these PRs is that they would be less costly to farmers who are the majority with little or no purchasing power (Peng and Hammond, 1979; Sanchez and Salinas, 1981) and has longer residual effects (Chien and Hammond, 1978) than processed phosphate fertilisers.

Minjingu PR (MPR) is among the PR deposits mined in Tanzania. The MPR, a sedimentary phosphorite in origin, is found in the northern of zone of Tanzania near Lake Manyara (Harris, 1981). Other PR deposits have been discovered at Songwe

(Songwe scarp carbonatite); Mbalizi (Mbalizi carbonatite and a close variant called Mbalizi fenite) and Panda Hills (Panda Hills carbonatite) in Mbeya (Mtuy, 1987).

The use of MPR in crop production is limited by its low reactivity and solubility in soils. The MPR is 100% water insoluble, hence its immediate availability to plants is extremely limited. In order for the MPR to be effective as a P fertiliser, the first requirement is that substantial amounts of the MPR should dissolve immediately after application and this can be achieved in soils with very strong acid reaction, very low levels of phosphorus and calcium. It has been recommended that PR be added to soils prior to planting. However, the time of application for maximum availability of P from MPR like many other PRs in various soils is still a subject of some degree of uncertainty. Many of the PR sources tend to vary widely in their agronomic effectiveness due to many factors that prevail in a particular PR-soil-plant-farming system which in turn determines its rate of dissolution and hence P availability to plants (Khasawneh and Doll, 1978; Bolland *et al.*, 1988). Furthermore, the rate at which it is applied also affect PR dissolution.

There is a need, therefore, to attempt to establish the appropriate time of application of PRs prior to planting and rates to be applied so as to attain optimal crop response to the PR applied. In view of the above, the present study was undertaken to study the influence of time of contact and rates of MPR on its dissolution or the release of P and

Ca for plant uptake. Therefore, this study was aimed at the following specific objectives:

(i) To asses the effect of time of contact between soil and MPR on the dissolution of MPR and consequently the release of P and Ca,

(ii) To asses the effect of MPR application rates on the dissolution of MPR,

(iii) To asses the effect of MPR on various chemical properties of the soil, and

(iv) To determine the optimal rate of application rate of MPR for optimal growth and yield of maize crop.

CHAPTER TWO

LITERATURE REVIEW

2.1 Origin and Mineralogical composition of Phosphate Rocks (PRs)

Phosphate rocks are claimed to originate from phosphorite deposited on the adjacent, somewhat more stable, mentary, weathering and biological processes (Cathcart, 1980). Subsequently, phosphate deposits have been grouped into marine phosphorite, apatite of igneous origin, residual deposits, phosphoritized rock and guano. According to McClellan and Gremillion (1980) these PRs have been found to occur as igneous, sedimentary and metamorphic depositions following their geological formations. PRs may contain apatite (calcium phosphate); aluminium phosphate; iron and aluminium phosphate; and some accessory minerals like siliceous and carbonates (McClellan and Gremillion, 1980; Hagin and Harrison, 1993). Whereas apatite minerals are reported to be most abundant in commercial PRs, their composition varies widely from the mineral fluorapatite to hydroxy apatite and minerals of francolite (Bolan *et al.*, 1993). It has been claimed that the carbonate apatite found in micro-crystalline structure (0.2 μm) which is the principle phosphate mineral in sedimentary PRs renders sedimentary deposits to be of higher economical importance.

A major draw back to the use of PRs for direct application has been the uncertainty of their agronomic effectiveness as they differ widely in their chemical reactivity in different soils (Khasawneh and Doll, 1978; Bolan *et al.*, 1993; Sale and Mokwunye, 1993).

2.2 Factors influencing the dissolution of phosphate rocks

2.2.1 Mineralogical and chemical composition

The reactivity of phosphate rocks utilized for direct application as sources of P varies with their mineralogical composition (Lehr and McClellan, 1972). The reactivity of sedimentary apatites which are the major sources of commercial PRs (McClellan, 1979), results from the degree of isomorphic substitution of phosphate by carbonate that occurs within the apatite crystal structure (Hammond *et al.*, 1986; Sanyal and Datta, 1991). Solubility of PR tends to increase as carbonate substitution for phosphate in apatite structure increases in accordance with theoretical considerations (Chien, 1977). Hagin and Harrison (1993) also inferred that the presence of carbonate minerals like calcite depresses the apparent solubility of the PRs in the conventional extraction solutions. Thus the chemical reactivity of the rock phosphate could be determined by the extent of isomorphic substitution within the crystal lattice/structure of the phosphate rock. Hedley *et al.* (1990) concluded that the most reactive PRs are those having a molar PO_4/CO_3 ratio of less than 5.

The Minjingu phosphate rock (MPR) which is found in Tanzania, Telemsi PR from Mali, Matam PR from Senegal and Tahoua PR from Niger have been classified as of medium reactivity in tropical Africa with respect to the rate at which the P contained in these PRs is released (McClellan and Notholt, 1986 as quoted by Sale and Mokwunye, 1993).

It has also been recognized that availability of P from phosphate rocks seem to be closely associated with the fluorine contents in PR materials (Bennet *et al.*, 1957). A general trend for the P availability in the PR has been observed to decrease as the percentage of fluorine in the rock increases. In view of this concept, PRs with low fluorine contents have been recommended for direct direct use as phosphate fertilizers. PRs may also contain other minerals which seems to influence the reactivity of the apatite when applied to soils. Presence of accessory minerals, like siliceous minerals may depress both the PR solubility and its reactivity in soils (Hammond *et al.*, 1986).

2.2.2 The particle size of PR materials

Lehr and McClellan (1972) noted that apart from isomorphic substitution, increase in solubility of PR increases with decrease in the size of the PR particles as a consequence of the increase in specific surface area of the PR particles. Direct application of the phosphate rock as a fertilizer material commonly requires grinding the rock to a fine powder (fine particles) that is reducing its particles to a size less than 100 mesh (150 μm) so as to enhance its solubility in soils. Chien and Hammond (1978a) in their study to evaluate the solubility of two granulated phosphate rocks over a range of granule sizes, found that the solubility decreased drastically as the granule size increased from the average diameters of 0.05 mm to 1.00 mm.

Generally, decreasing particle size by grinding tends to increase the surface area of PR particles exposed to and in contact with the soil and hence increase the rate of P release from the PR. Khasawneh and Doll (1978) observed that by increasing the fineness of PR particles by grinding up to 100 mesh (< 150 µm) often increased P availability but finer grinding seemed not to influence it.

Minjingu PR (MPR) like many other sedimentary PRs tend to be microcrystalline with large specific surface areas which render them more reactive in comparison to igneous PR like Songwe scarp (SSC) and Mbalizi carbonatite (MC) both of igneous origin which are coarsely crystalline. Mnkeni *et al.* (1992) conducted incubation studies on two soils of Morogoro district to study the dissolution of PRs found in Tanzania, namely: SSC, MC and MPR and the results showed that MPR released more P than SSC with incubation, indicating that it was more reactive. The higher solubility of MPR as compared to the others was attributed to the micro-crystalline structure and low fluorine content of the MPR.

2.2 3 Soil characteristics

2.2.3.1 Soil pH

Dissolution of PR, Minjingu PR inclusive, depends also on the soil pH. Phosphate rock dissolves more readily in acid than in alkaline soils (Peaslee *et al.*, 1962; Fenster and Leon, 1978, Mackay and Syers, 1986; Kanabo and Gilkes, 1987). An acid pH is a pre-requisite for the dissolution of PR in soil, based on the fact that dissolution of the apatite relies on the net supply of protons (Kanabo and Gilkes, 1987; Robinson *et al.*, 1992). Kanabo and Gilkes (1987) observed that PR dissolution was more closely related to the amount of titratable acidity than to pH *per se*. The driving force for the dissolution of the carbonate apatite contained in the PR in acid soils, is the neutralization reaction between soil H^+ and the PO_4^{3-}, $H_2O + CO_2$, HF, and H_2O, respectively (Chien, 1993 cited by Sale and Mokwunye, 1993). Ultimately this situation leads to higher effectiveness of PR in acid soils. Troeh and Thompson (1993) thus commented that rock phosphate shouldn't be considered as a fertilizer unless the soil is acid.

2.2.3.2 Soil texture and structure

Soil texture seems to be closely related to cation exchange capacity (CEC) of a soil. Sandy soils with low CEC do not provide a sink for Ca ions released from PR, hence PR dissolution is slowed (Khasawneh and Doll, 1978). Hughes and Gilkes (1986) observed more dissolution of PR as the silt content increased for soils from Australia, Nigeria and South America. It was suggested that this might have been associated with the higher chemical reactivity of the silt fraction relative to the inert (quartz) sand size-minerals in soils (Kanabo and Gilkes, 1988b).

Similarly, Kanabo and Gilkes (1988b) in their study to assess the effect of soil texture on the dissolution of North Carolina phosphate rock, found that ΔP (total fertilizer phosphate dissolved) increased with increasing content of < 45 µm size particles. They noted that $NaHCO_3$-extractable P (ΔP_b) also increased with the percentage of < 45 µm size fraction, with about 20% of ΔP being recovered as ΔP_b. A smaller proportion of dissolved P was soluble in $NaHCO_3$ for the soil comprising only the < 45 µm size particles. They finally concluded that the increase in the total fertilizer phosphate dissolved (ΔP) with increased percentage of < 45 μm size soil particles was probably due to *inter alia* the high P-sorption, Ca-sorption and the pH buffering capacity of the fine grained soil constituents.

Apparently, a good soil structure provides ideal conditions to micro-organisms to decompose soil organic matter (Welte, 1978). The hydrolysis of soil organic matter in tropical soils provides a substantial sink for Ca through the supply of Ca chelating substances that can reduce the activity of Ca ions in the soil solution (Chien, 1979). The reduced Ca^{2+} activity consequently enhances the dissolution of the PR, hence the argument that organic matter increases the rate of PR dissolution in soils.

2.2.3.3 Soil Ca and P contents, and P-sorption capacity

Dissolution of PR has also been observed to be favoured by low concentrations of phosphate and Ca ions in the soil solution (Hammond *et al.*, 1986; Robinson and Syers, 1990). Following the law of mass action, soils with high Ca contents would slow down the dissolution of PR because the soils also release Ca ions (Hammond *et al.*, 1986).

High capacity of the soil to adsorb P and Ca has been found to promote the dissolution of phosphate rock (Chien *et al.*, 1980 cited by Hughes and Gilkes 1986; Mackay *et al.*, 1986). It has been pointed out by Di *et al.* (1994c) that although PR materials may dissolve quickly in a higher P retaining soil, a high proportion of the P initially dissolved may be rapidly retained by the soil components hence not available to crops.

2.2.3.4 Soil organic matter

Soil organic matter is among the other soil factors that have been reported to enhance PR dissolution. The hydrolysis of soil organic matter in soils provides a sink for Ca^{2+} through the formation of Ca-chelates, hence reducing the activity of Ca^{2+} in the soil solution. Through such a complex compound formation between organic matter and Ca ions, the dissolution of PR in the soil is enhanced (Chien, 1979). Robinson and Syers (1992) pointed out that a provision of a sink for Ca in soils would lead into small concentration of Ca in soil solution thereby promoting more dissolution of PR. Results from application of 5 tons/ha of organic materials (manure and compost, respectively) mixed with MPR at the rate of 400 mg P kg^{-1} soil, enhanced the release of P from MPR, and manure was reported to be more effective (Ikerra,1986).

2.2.4 Effect of soil moisture

Soil moisture is often cited as one of the important factors that affect the dissolution of PR and its agronomic effectiveness as PRs will not dissolve in dry soils (Sale and Mokwunye, 1993). Higher rainfall often leads to a higher effectiveness but it is not clear as to whether the effectiveness of PR is more or less affected than water soluble P sources in this respect. It is also not clear as to whether this is a direct or an indirect effect, as soils in higher rainfall areas often have lower pH, lower amounts of available

Ca, and higher amounts of organic matter and all these factors are known to enhance the dissolution hence agronomic effectiveness of PRs. However, the high leaching indices would promote PR dissolution by facilitating the removal of the products of dissolution away from the surfaces of the PR particles. This may provide the principle mechanism for removing calcium from the system in areas of high rainfall with subsequent extensive leaching.

2.2.5 Plant factors

Acidification in the plant's rhizosphere environment is one of the mechanisms that have been suggested to enhance the release of P from PR (Flach *et al.*, 1987; Bolan and Hedley, 1991) and to account for the differences in the ability of various crop species to utilize PR. It has been argued that an excess absorption of cations over anions by plant roots would result in a loss of equilibrium inside and outside the plant roots and most likely, the plant roots would extrude H ions to maintain the equilibrium. This has been reported to occur in situations where legumes actively fix N_2 or plants take up and assimilate predominantly ammonium N (Bolan and Hedley, 1991). Accumulation of H ions in the rhizosphere surrounding root surfaces, result in an increase in the rate of dissolution of adjacent PR particles. Concurrent with the enhancement of microbial activities in the rooting zone, net microbial immobilization of P and excretion of organic acids from microbes is enhanced which in turn gives rise to more dissolution of phosphate rock (Bolan and Hedley, 1991).

Also a mechanism of high rooting density *per se* stimulates PR dissolution as it tends to bring about a shift in equilibrium of a Ca-phosphate compound following a high uptake of Ca and P (dissolution products) from the soil solution surrounding the surfaces of PR particles. According to Flach *et al.* (1987) high Ca uptake patterns are responsible for improved responses of certain plants to applied PRs.

2.2.6 Agronomic practices

2.2.6.1 Placement methods

The method of PR placement has a marked impact on PRs dissolution hence their effectiveness as P sources. The availability of P from PR depends on the probability of plant roots encountering the 'localised low concentration pockets' of soluble P around the dissolving PR particle (Khasawneh and Doll, 1978; Hammond *et al.*, 1986). It has been reported that the dissolution of PR would be increased if the PR is broadcasted and incorporated into the soil surface layers. Applying PRs in concentrated bands results in a reduction in the dissolution rate of PR, presumably as a result of an increase in the levels of Ca and OH ions around the dissolving particles. Thus for a PR to be most effective it should be broadcast on the soil surface, and subsequently incorporated into the soil (plough layer).

2.2.6.2 PR application rates

PR application rates have been found to affect PR dissolution in soils. Decrease in the amounts of released P and Ca from a dissolving PR when high rates of PR are added to soils under incubation studies have been reported. Hughes and Gilkes (1986) noted that an increase in the level of rock phosphate in most soils resulted in a smaller proportion of dissolving PR. This trend was confirmed by the results in soil classified as Haplorthox (from South America) where the percentage dissolution of PR after 31 days was 27% when 500 $\mu g\ Ca\ g^{-1}$ was added, but was only 4% when 12,500 $\mu g\ Ca\ g^{-1}$ was added as PR.

Di *et al.* (1994b) found that the percentage dissolution of PR was greater at lower application rates than at higher application rates. This was also confirmed by Dodor *et al.* (1999) in their study conducted to evaluate the dissolution of phosphate rock fertilizers in some soils of Okinawa (Japan). They reported a general decrease in percentage dissolution of PR as the application rates were increased, although absolute amounts of dissolved PR increased with increasing rate of application. The decrease in PR dissolution with increasing rates of PR application could be due to the limited supply of protons in relation to the amounts of PR and the lack of sink for the P and Ca ions at high levels of PR application rates.

2.2.6.3 The effect of time of application

Applying PRs well ahead of the planting of the crop has often been recommended so as to allow time for dissolution to take place and increase the rate of P uptake from PRs (Ellis *et al.*, 1955 cited by Sale and Mokwunye, 1993). Also Semoka (1988) cited by SFI (2000) reported similar dissolution results with Minjingu, Njelenje and Mbalizi phosphate rocks as compared to TSP. The results showed that P released from Minjingu and Songwe rock phosphates increased with soil-PR equilibration time (Semoka, 1988). Through such observations, then it could be concluded that P dissolution from rock phosphate increases with time of contact between rock phosphate and soil.

However, Chien *et al.* (1990), reported that such practices will be counter-productive in tropical soils that are acidic with high P-sorption capacities because the P released from the PR would have more time to react with the soil constituents, thereby becoming less available for plant uptake. These deductions were also found to agree with the findings obtained by Fardeau *et al.* (1988). In their study it was noted that the availability of both water soluble and insoluble P sources decreased with time of contact between PR and soil depending on the P fixation capacity of the soil. The amounts of P fixed can be avoided by ensuring that the contact time between soil and PR is as short as possible. Further, the amounts of P fixed could also be reduced by applying the fertilizer at planting time so as to enable the plant roots to compete with the soil P adsorption sites for the P ions that are released during the dissolution of the PR.

Chien *et al.* (1990), noted that the effectiveness of North Carolina PR was the same whether the PR was applied at planting or six weeks before planting maize seeds in a soil with lower P-sorption capacity. However, in a soil with higher P-sorption capacity, the effectiveness of PR was reduced when it was applied six weeks before planting. Likewise Hammond *et al.* (1986) reported the same results which were obtained from

Latin American soils under field conditions. However, Hughes and Gilkes (1986) found a very small amount of rock phosphate dissolved (<5%) at zero day, whereas, a rapid dissolution was found to occur within one day. This was followed by a considerable slower dissolution up to 124 days of PR and soil contacts. This is in line with the findings made by Robinson and Syers (1991) that in most of UK soils used to study and examine the dissolution of Gafsa phosphate rock (GPR), the dissolution of GPR continued up to 40 days after which there was a negligible increase in the released P.

Provided that conditions are favourable for dissolution, PR will continue to dissolve over time and maintain the supply of plant-available P. The PR generally have more lasting residual effect because of this gradual dissolution as compared to water soluble P fertilizers. Mnkeni *et al.* (1992) obtained similar results, where the extractable P in TSP treated soil samples (pH = 5.5) decreased with time up to 30 days of incubation, while for Minjingu PR applied to the same soil the extractable P values increased with incubation time up to 45 days. Purnomo and Black (1994) found that application of North Carolina PR to chromic luvisol 30 days prior to sowing resulted in higher Colwell extractable P than when applied at sowing.

2.3 Crop Response to PR

Several studies have shown different responses of crop plants to direct applications of phosphate rocks. Chien *et al.* (1990) reported better performance of PR with respect to TSP in Hartsells soil (4.2% organic matter) than in Mount view soil (1.8% organic matter) based on dry matter yields of maize crop. Organic matter, therefore, acted as a sink for Ca in soils. Mnkeni *et al.* (1991) obtained significant maize crop responses to Minjingu PR applications to some soils of Morogoro with low P (< 6.5 ppm) and low pH (< 5.2) values. The increase in the amounts of MPR-P from 40 to 120 mg/kg led to significant higher dry matter yields. However, there were no significant responses to MPR applications to other soils, with pH values ≥ 6.6 with comparable P levels (6.13 ppm P).

Similarly, a rye (*Secale cereale*) plant grown in a soil of pH of 5.0, was found to take 238% more P from PR than when the soil was limed to a pH of 6.5 (Jones, 1948 cited by Tusekelege, 1997). However, despite of such positive results, contradicting results have also been reported by Bennet *et al.* (1957) who worked with maize crop as a test plant, managed to obtain grain yield response to PR through liming from pH 5.0 to 5.8. Such a response has been deduced to be associated with amelioration of Al toxicity through precipitation of free Al as hydroxyl-Al species as pH is raised above 6.0 (Amarasiri and Olsen, 1973).

Hammond (1978) observed an increase in maize dry matter yields particularly when mesh size was reduced from 0.15 to 0.075 mm for North Carolina PR applied to acid soils. Keleg *et al.* (1978) found no significant increase in Sudan grass (*Sorghum sudanance*) dry matter yield following the application of Gafsa PR to clay loamy and sandy soils indicating that soil texture had significant influence on the dissolution of PR.

Purnomo and Black (1994) obtained no significant response by wheat (dry matter yields) when North Carolina phosphate rock was applied to a red earth (chromic luvisol) before or at sowing time. The observations by Purnomo and Black (1994) contradict with those of Paitnak *et al.* (1974) who obtained significant rice response to Mussorie phosphate rock applied to soils 30 days prior to sowing the rice. The above contradicting results would be attributed to crop and soil differences. However, Purnomo and Black (1994) used a red podzolic (chromic luvisol) soil which had a lower P-status, lower exchangeable Ca^{2+} concentration, was more acid and had a higher exchangeable Al^{3+} concentration than the red earth soil used in their previous study. They found that application of NCPR 30 days before sowing resulted in lower wheat dry matter yields than when applied at sowing. The higher concentration of exchangeable Al contained in the soil used in the latter study was explained as the one which reduced the P concentration in the soil solution (through P-fixation) and hence reduced dry matter yields.

CHAPTER THREE

MATERIALS AND METHODS

An incubation glasshouse pot experiment was conducted at the Sokoine University of Agriculture (SUA) Morogoro Tanzania. This study was done to evaluate the effect of time of contact between Minjingu phosphate rock and soil, and MPR rates on dissolution of MPR when applied to an Oxic (Kanhaplic) Haplustults and subsequently maize response to the MPR applied to the soil in question.

The rates of MPR applied were: 0, 0.80, 1.20, 1.60 and 2.30 g MPR/ 4 kg of soil (per pot) equivalent to 0, 50, 75, 100, and 150 Kg P/ha. The times/ periods of contact between the MPR and soil were 120, 90, 60, 30 and 0 days prior to the sowing of the maize (*Zea mays*. L variety Staha). During the incubation/equilibration periods, the soils in the pots were maintained at about field capacity throughout the growing period of the maize plants using distilled water.

3.1 Soil sampling and preparation

Four hundred kilograms of a composite soil sample (0-30 cm depth) were collected from the SUA farm which is located at 6°51' S and 37°39' E, and at an altitude of approximately 550 m above sea level. The experimental soil has been classified as Oxic (Kanhaplic) Haplustults (Kaaya *et al.*, 1994) equivalent to Dystric Nitosols according to FAO-UNESCO (1974). The composite soil sample was air dried, and ground to pass through 8 mm sieve for glasshouse pot experiment. However, a representative soil sub-sample was taken and ground to pass through a 2 mm stainless steel sieve to be used for chemical and physical analyses in the laboratory.

3.2 Soil analysis

The selected relevant chemical and physical characteristics of the soil sub-sample were determined according to the following procedures. Particle size distribution of the soil was determined using the hydrometer method (Gee and Bauder, 1986) and subsequently textural classification was done according to FAO (1990). Soil pH was measured in 1:2.5 soil: water suspension and soil: 0.01 M $CaCl_2$ suspension using a pH meter (McLean, 1982). Available P was extracted by the Bray-1 procedure (Bray and Kurtz, 1945) and P concentration in the extract determined by the ascorbic acid-molybdate blue method (Murphy and Riley, 1962). Exchangeable cations (K^+, Ca^{2+}, Mg^{2+} and Na^+) were extracted by ammonium acetate then determined by atomic absorption spectrophotometer (Thomas, 1982). Cation exchange capacity of the soil was determined by the ammonium acetate (buffered at pH 7.0) saturation method (Thomas, 1982). Exchangeable Al and exchangeable acidity were determined according to the KCl method described by McLean (1982). Organic carbon content in the soil was determined by the Walkley and Black method (Nelson and Sommer, 1982). The percentage organic matter content was estimated by the Van Bermnelen factor of 1.724 (Nelson and Sommer, 1982). Total nitrogen content in the soil was determined by the micro-Kjeldahl digestion distillation procedure (Bremner and Mulvaney, 1982).

3.3 Glasshouse pot experiment

Seventy five four kilogram soil sample portions of the composite soil sample sieved through 8 mm sieve were weighed into five litre capacity plastic pots with holes at the bottom (loosely plugged with cotton wool) for drainage. The seventy five, five litre capacity plastic pots each with four kilograms of soil were divided into five batches of fifteen pots each as follows:

Batch I: 120 days of incubation: Fifteen of the 75, four kilogram soil sample portions in the five litre capacity plastic pots were thoroughly mixed with MPR at the rates of 0, 0.80, 1.20, 1.60 and 2.30 g MPR/4 kg soil. Distilled water was added to the soil to about field capacity. Any solution draining out from the soil in the plastic pots was collected in the saucers that were placed under the plastic pots and returned back to the soil. Treatments were replicated three times. Soils in the pots were incubated at about field capacity (under glasshouse conditions) throughout the study (120 days).

Batch II: 90 days of incubation: Fifteen of the remaining 60, four kilogram soil sample portions in the five litre capacity plastic pots were treated as above (batch i) and incubated at about field capacity for 90 days.

Batch III: 60 days of incubation: Similarly, fifteen of the remaining 45, four kilogram soil sample portions in the five litre capacity plastic pots were treated as above (batch ii) and incubated at about field capacity for 60 days.

Batch IV: 30 days of incubation: Fifteen of the remaining 30, four kilogram soil sample portions in the five litre capacity plastic pots were also treated as above (batch iii) and incubated at about field capacity for 30 days.

Batch V: Zero day of incubation (reference time of contact): Fifteen of the last remaining 15, four kilogram soil sample portions were treated as above (batch iv).

3.4 Data collection

Immediately at the end of the incubation periods, which were on the same date, soil sub-samples were taken from each pot for every batch, air dried, ground and sieved through 2 mm sieve. The above soil sub-samples were used for the determination of pH, exchangeable acidity, exchangeable Al, extractable P and exchangeable Ca. Immediately after soil sampling from the pots, six maize seeds were planted in each pot and thinned to three plants seven days after germination/emergence. Then after two weeks, nitrogen fetilizer in the form of NH_4NO_3 was applied into the pots at the rate of 120 kg N/ha, respectively. The plants were left to grow for thirty days. At the age of thirty days, the maize plant portions above soil level in pots were harvested accordingly, washed with distilled water and dried to constant weights (70 °C) for dry matter determinations. After determination of the dry matter yields, samples were ground into fine powder for the determination of Ca and P contents in the maize plants (%) following the procedures as outlined by Jones and Case (1990).

3.4.1 Determination of MPR dissolution

The ΔBray-1 P method was employed to measure the difference in extractable P between the MPR treated and untreated soils. Then the percentage of Minjingu rock phosphate that has dissolved was calculated from ΔP values.

3.5 Data analysis

The soil analytical data for the sub-samples of the soils collected at the end of each incubation period, dry matter yields, %P and Ca contents, and their uptakes by the maize plants were statistically analysed using MSTATC computer program. All analyses of variance (ANOVA) were performed basing on the 5^2 factorial experiment in completely randomized block design layout (Snedecor and Cochran, 1989). Whereas, the variables' means were separated according to Duncun's New Multiple Range Test (DNMRT). The model used for the statistical analysis of the data was:

$$Y_{ijk} = \mu + \tau_i + \gamma_j + \beta_k + (\tau\gamma)_{ij} + (\tau\beta)_{ik} + (\gamma\beta)_{jk} + (\tau\gamma\beta)_{ijk} + \in_{ijkl}$$

Where:

Y_{ijk} = Dissolution of MPR

i=1,2,....,a (time)

j=1,2,....,b (rate)

k=1,2,...., k (block)

l=1,2,...., n (replications)

μ= overall mean effect

τ_i= effect of i^{th} level of time

γ_j = effect of j^{th} level of MPR application rate

β_k = effect of k^{th} block

$(\tau\gamma)_{ij}$= the two factor (A x B) interaction effects

$(\tau\beta)_{ik}$= Time and block interaction effects

$(\gamma\beta)_{jk}$ = MPR rate and block interaction effects

$(\tau\gamma\beta)_{ijk}$ = interaction effects between two factors and blocks in combination

$\in_{ijkl}$ is the random error component.

Multiple regression analysis was also done (Snedecor and Cochran, 1989) to evaluate how independent variables (soil-MPR equilibration time and rates of MPR) are related to Y (MPR dissolution). The regression model of analysis used was as follows:

$$Y= \beta_0 + \beta_1X_1 + \beta_2X_2 +\in$$

Where:

Y= Dissolution of MPR

β_0= Y-intercept when X_1 and X_2 are zero values

β_1 and β_2 = regression coefficients

X_1 and X_2 = Time and MPR rates, respectively.

$\in$ = is random variable i.e. has a normal distribution with mean 0 and variance of the regression of Y on X_1 and X_2.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Physical and chemical properties of the Oxic Haplustults

Some of the physical and chemical properties of the Oxic Haplustults were as presented in Table 1 and Appendix 1. Based on the percentage sand, silt and clay particles in the Oxic Haplustults, the textural class of the soil was designated as clay (FAO, 1990). The clay textural class of the soil would have some influence on the moisture retention, transmission and cation exchange and retention capacity of the soil (Hillel, 1982). However, the magnitude of the influence on the above properties would be dependent on the type of clay minerals and their mineralogical composition. Most highly weathered tropical soils like Oxic Haplustults are dominated by 1:1 clay minerals and some considerable amounts of Al and Fe oxides and hydroxides, hence their low CEC-values.

The Oxic Haplustults had pH values of 4.9 and 3.9 in water and 0.01 M $CaCl_2$, respectively. According to the categorization by Landon (1991) the low pH is rated as low and strongly acid; that is below soil 5.5. The very low pH of the soil could be attributed to the extensive weathering of the soil, extensive leaching and predominance of exchangeable Al^{3+} and H^+ on the exchange sites and in the soil solution (Thomas and Hargrove, 1984).

The NH_4F-HCl extractable phosphorus (Bray-1-P) for the soil was found to be 2.9 mg P/kg soil. According to the categorization by Landon (1991), the extractable phosphorus for the soil is rated as low. The low level of Bray-1-P in the Oxic Haplustults could be due to low levels of P in the soils' parent materials and conversion of P into forms not extractable by the Bray-1-P reagents because of the strong acidic nature of the soil (Tisdale *et al.*, 1993).

The Oxic Haplustults organic carbon (1.3%), organic matter (2.2%) and total nitrogen (0.1%) were low in accordance with Landon (1991) ratings. This is apparently due to higher rate of organic matter transformations (through oxidation, mineralization processes and the like) which normally takes place in tropical soils. Further the non-return of crop residues and weeds/grasses could account for the low organic matter and total N-contents in the Oxic Haplustults.

The amounts of exchangeable bases were generally low (except K) ranging from 0.15 to 2.32 Cmol(+)/kg soil. The lowest amount of these exchangeable bases was observed for Na, whereas the trend of the others was as follows: Mg (2.32); Ca (2.02); and K (0.65), as shown in Table 1. The low values of these bases Ca, Mg and Na in particular, indicates that the soil is extensively weathered, with low pH and that most of the bases have been leached out/displaced from the exchange sites.

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As according to Landon (1991), the CEC of the experimental soil was ranked as low (i.e. 13.4 Cmol(+)/kg soil). The low CEC can be attributed to the low amount of organic carbon/organic matter and probably the nature of the clay minerals contained in the soil. In view of this, the soil is liable to respond to fertiliser applications. Similarly, the base saturation was 38.4% showing that the soil is less fertile following the categorization made by Landon (1991) that soils with BSP < 50% (Dystric = less fertile status) are categorized as of low fertility status. The low fertility status of the Oxic Haplustults corresponds to the Al^{3+} contents, low soil pH and relatively low amounts of exchangeable bases to neutralize the soil acidity.

On the other hand, the exchangeable acidity and Al values of the soil were 1.59 and 1.01 Cmol(+)/kg soil, respectively, are generally low. The Al saturation (Al: CEC) was 7.5% which still can affect sensitive crops despite of being less than 50%. Probable fertilizer problems associated with soils containing such properties includes reduced availability of P.

Table 1. Some of the physical and chemical properties of the Oxic Haplustults

Parameter	Unit
pH $_{(water)}$	4.9
pH ($CaCl_2$)	3.9
Bray-1 P (mg kg^{-1})	2.9
Organic C (%)	1.3
Total N (%)	0.1
Exchangeable bases [Cmol(+) kg^{-1} soil]:	
Ca	2.02
Mg	2.32
K	0.65
Na	0.15
CEC (NH_4Ac) [Cmol(+)kg^{-1}]	13.4
% Base saturation	38.4
Titratable acidity [Cmol(+)kg^{-1}]	1.59
Exchangeable Al [Cmol(+)kg^{-1} soil]	1.01
Particle size distribution:	
Sand (%)	30.9
Silt (%)	5.3
Clay (%)	63.7
Textural class	Clay

4.2 MPR dissolution

4.2.1 Phosphate released

The amounts of phosphate released (Bray-1-P) as a consequence of the dissolution of the MPR mixed with the Oxic Haplustults at various incubation (contact) periods and rates of MPR applied to the soil were as presented in Table 2a and 2b, and Appendix 2. The amounts of released P from dissolution of the MPR increased with increasing rates of MPR applied at each of the incubation period. Results indicate that the relative increase in dissolution followed the order: 50 < 75 < 100 < 150 kg P/ha in all incubation periods (Appendix 2). However, the amounts of P released at different rates of MPR added to the Oxic Haplustults, increased with increasing period of incubation up to about 75 days of equilibration/incubation, then tended to decline with further increase in period of contact between soil and MPR. The amounts of dissolved MPR ranged from 1.17 to 13.11 mg P/kg and 10.74 to 15.91% as regards to extractable P and ΔP% values, respectively (Table 2a and Table 2b). The increases in Bray-1-extractable P at various incubation periods and with increasing rates of MPR application were significant at $P \leq 0.05$ (Table 2a). The low soil pH value, low extractable P and exchangeable Ca (Table 1) definitely have been the driving forces for the significant MPR dissolution.

In contrast to the results obtained from this study, however, other researchers reported decrease in percentage dissolution with increasing rate of PR application (Hughes and Gilkes, 1986; Di *et al.*, 1994b; Dodor *et al.*, 1999). Observations made from this study however, indicate that the amounts of MPR applied to the soil were not very high to the extent that it could have been close enough to make an overlap of dissolved Ca and P ions zones and exhaustion of protons to slow down the rate of MPR dissolution (Rajan, 1996 cited by Dodor *et al.*, 1999). On the other hand, the findings from the present study conform with those reported by Ikerra (1986), Mackay *et al.* (1986), Mnkeni *et al.* (1992), Mwakisimba (1999) and Semoka (1988), who reported increased PR dissolution with increased rates of application of MPR hence increased amounts of extractable Bray-1-P.

However, the findings from the current study have shown low recovery rates of dissolved P from MPR as compared to those reported by the previous researchers above. Probably such low recovery rates of MPR-P may be mainly related to differences in the amounts of MPR applied, the chemical and mineralogical composition of the soil constituents (Oxic Haplustults) and the P retention capacity of the soil in question. The Oxic Haplustults has been reported to have high P fixation capacity (Babili, 1999) and this could be attributed to the dominance of the 1:1 clay minerals and hydrous oxides of Al and Fe in the clay fraction of the soil, and significant amounts of exchangeable Al^{3+}. In addition, the contradiction could probably be attributed to the fact that some results thus reported were based on field trials where PR was banded, while in this study the MPR was thoroughly mixed with the soil. The different recovery rates were then attributed to the interaction between MPR and soil consequent to the thorough mixing of MPR and soil increased the extent of contact between MPR and soil hence more fixation of the P released through the dissolution of MPR.

The relative gradual decrease in the amounts of released P beyond the period of 75 days may be associated with the increased time for reaction of the released P with Al and Fe oxides in Oxic Haplustults because of the chemical reaction dynamics in soils. Also the hydrolysis reaction is not instantaneous hence the gradual decrease in available P with increased time of contact/equilibration between the MPR and the soil. It has been reported that 1 meq of exchangeable Al per 100 g of soil when hydrolysed can fix up to 102 ppm P (Sanchez and Uehara, 1980).

In this study the results, imply that the maximum time for MPR application before planting should not be more than 75 days. The 75 days of MPR-Soil incubation could be prescribed as the optimal time period for MPR to be an effective and economic P fertilizer. However, the suggested optimal time of contact between MPR and soil for optimal MPR dissolution should be researched upon further at high rates of applied MPR both under glasshouse and field conditions and when the MPR is banded and broadcasted.

Table 2a. Effect of MPR rates and MPR-Soil equilibration periods on Bray-1 phosphorus (mg P/kg soil)

MPR rates (kg P/ha)	Equilibration period (Days)				Mean effects of MPR rates
	30	60	90	120	
0	1.353 i[1]	1.353 i	1.038 i	0.9364 l	1.170 e[1]
50	4.244 jk	4.227 jk	3.559 k	3.388 k	3.854 d
75	5.648 hi	6.296 gh	5.096 ij	4.926 ij	5.491 c
100	7.293 ef	8.696 d	7.808 de	6.843 fg	7.660 b
150	14.25 a	14.13 a	12.64 b	11.40 c	13.11 a
Mean effects of equilibration periods	6.558 a[2]	6.941 a	6.028 b	5.498 c	
LSD value	± 0.4042				
CV (%)	8.75				

LSD values for interaction (equilibration periods × MPR rates effects) and that of MPR rates' effects are: ± 0.9038 and ± 0.4519, respectively.

1, 2 = all means followed by the same letter do not differ significantly ($P \leq 0.05$) according to DNMRT.

Table 2b. MPR dissolution (ΔP%) as effected by equilibration periods and application rates

Incubation/equilibration period (days)	Δ Bray - P(%)
30	13.16 ab[1]
60	14.10 a
90	12.48 bc
120	11.55 c
MPR rates applied (mg P/kg)	
25.0	10.74 c[2]
37.5	11.52 c
50.0	13.12 b
75.0	15.91 a

CV % = 5.47

LSD value = ± 1.122

S E M = 0.3507

SEM = standard error of the mean.

1,2 = all means followed by the same letter are not significantly different ($P < 0.05$) according to DNMRT.

4.2.2 Estimation of MPR dissolution

Simple and multiple regression analyses were done to trace back the overall influence of incubation times and application rates on the extent of MPR dissolution. As regards to the multiple regression, these two factors together explained about 86.8% ($P < 0.001$) of the variation in the ΔBray-1-P from MPR. However, the incubation/equilibration period factor was found to be non significant ($P > 0.05$) and negatively related ($r = -0.321$) with the MPR dissolution (%) and explained only about 10.3% of the variation in MPR dissolution (%). The MPR rates data were found to be highly significantly correlated ($r = 0.875$) with the MPR dissolved P (%). This relationship was significant at $P < 0.001$. Similarly, the MPR rate variable managed to explain about 76.6% of the MPR dissolution trend in the Oxic Haplustults.

Thus such observations confirm the arguement that with the increase in time of soil and MPR contact leads into a reaction of the MPR released P with the Al and Fe hydrous oxides in the soil hence become fixed and unavailable to plants (Hughes and Gilkes, 1994). Nevertheless, the progressive increase in amounts of P released from MPR following the increase in MPR rates was probably attributed to the higher amounts of protons in the exchange sites as compared to the lower amount of the MPR applied to saturate them hence an adequate sink for P (Robinson and Syers, 1992).

4.3 The effect of MPR dissolution on some chemical properties of the soil

4.3.1 Exchangeable acidity

Table 3 gives the results of exchangeable acidity resulting from different levels of MPR applied at different incubation times. The results showed a slight decrease in exchangeable acidity with the decrease in incubation time as it varied from 1.27 (after 30 days) to 1.30 Cmol(+)/kg soil (after 120 days). It also decreased substantially as compared to the control with the increase in amount of MPR applied to the soil, that is dropped from 1.61 to 1.00 Cmol(+)/kg of soil (Table 3).

Despite of such a slight decrease in exchangeable acidity following the decrease in the time of soil and MPR contact, these results were found to be non significant at $P = 0.05$. The increase in MPR application rates significantly ($P \leq 0.05$) reduced the exchangeable acidity/proton supply capacity. These kinds of results are consistent with the dissolution trends as described in the previous sections above as it relatively decreased with increase in equilibration period beyond about 75 days. Further the released Ca ions from the dissolving $CaCO_3$ component of the MPR, significantly influenced the binding sites of Al on the exchange sites and neutralized the H^+ in the soil and subsequently reduced the amounts of the released protons from the exchange sites (Mnkeni *et al.*,1992; Sale and Mokwunye, 1993).

Table 3. Effect of MPR-Soil equilibration periods and MPR rates on exchangeable acidity (Cmol(+)/kg soil)

MPR rates (kg P/ha)	Incubation periods (Days)				Mean effects of MPR rates effects
	30	60	90	120	
0	1.55 bc^1	1.54 c	1.70 a	1.60 ab	1.61 a^1
50	1.41 d	1.35 de	1.31 ef	1.38 de	1.36 b
75	1.23 fg	1.25 fg	1.30 ef	1.29 ef	1.26 c
100	1.17 g	1.22 fg	1.15 g	1.18 g	1.18 d
150	1.00 h	1.02 h	0.97 h	1.01 h	1.0 e
Mean effects of equilibration periods	1.27 a^2	1.27 a	1.29 a	1.30 a	
LSD value	± 0.040				
CV (%)	4.01				

LSD values for interaction (incubation periods × MPR rates) means and that for MPR rates effect means are: ± 0.0905 and ± 0.04587, respectively.

1,2 = all means followed by the same letter do not differ significantly ($P \leq 0.05$) according to DNMRT.

4.3.2 Soil pH

The soil pH measured in water after different incubation/equilibration periods and at different rates of MPR were as presented in Table 4. The soil pH values generally increased from 4.9 to 5.0 after 30 and approximately after 75 days of MPR-Soil equilibration, there was a decrease in pH. These findings were statistically significant ($P \leq 0.05$), whereby 30 and 60 and did not differ significantly as it was for 90 and 120 days of incubation, respectively (Table 4). The increase in the amount of Minjingu PR, raised the soil pH values fairly higher than that measured from MPR untreated soils and this increase was significant at $P < 0.05$. Similarly, this trend of results markedly agrees with that of extractable Ca increase in Table 5. Slight increase in pH values was probably attributed to the amounts of MPR applied to the soil, which were not that high.

Table 4. Effect of MPR-Soil equilibration periods and MPR rates on the pH$_{water}$ of the Oxic Haplustults

MPR rates (kg P/ha)	Equilibration period (Days)				Mean effects of MPR rates
	30	60	90	120	
0	4.93 fg[1]	4.98 def	4.69 h	4.73 h	4.83 e[1]
50	4.99 de	4.97 def	4.89 g	4.89 g	4.94 d
75	5.01 cd	4.99 de	4.94 efg	4.92 fg	4.96 c
100	5.05 abc	5.02 bcd	4.92 fg	4.97 def	4.99 b
150	5.07 ab	5.09 a	5.00 cd	5.00 cd	5.04 a
Mean effects of equilibration periods	5.01 a[2]	5.01 a	4.89 b	4.90 b	
LSD value	± 0.02338				
CV (%)	0.67				

LSD values for the interaction (Equilibration periods and MPR rates) effects and that for MPR rates are: ± 0.05227 and ± 0.02613, respectively.

1,2 = all means with the same letter are not significantly different ($P < 0.05$) according to DNMRT.

These results due to the incubation/equilibration periods conform with those obtained by Hughes and Gilkes (1984), Ikkera (1986) and Mnkeni *et al.* (1992). Mnkeni *et al.* (1992) reported a substantial increase in pH (water) value after 30 days of incubation, from 6.2 (control soil) to 6.4 when 400 μg P/g applied as MPR to Magadu 1 (used for pasture). Similarly the soil pH increased from 5.6 to 5.7 when 36 μg P/g as MPR was applied to Magadu 2 soil (used for maize). There was a general decrease in pH with increase in days of soil-MPR fertiliser contacts. Apparently, Ca ions released from MPR dissolution due to incubation period(s), positively influenced the pH of the soil.

Based on the observations made by Mnkeni *et al.* (1992), the results from this study indicates that free $CaCO_3$ being more soluble than the apatite component neutralised the H ions in the soil which would otherwise have decomposed the apatite. Further the MPR dissolution increased the Ca content in the treated soils as compared to the controls.

4.3.3 Soil exchangeable Ca

Table 5 shows the changes in amounts of released Ca from the MPR which were determined at different incubation/equilibration periods and MPR rates. It's noticeable that, although there were no significant ($P = 0.05$) differences in exchangeable Ca at different incubation periods, exchangeable Ca slightly tended to decrease with the increase in soil-MPR equilibration time. The mean amounts of exchangeable Ca relatively decreased from 3.38 to 3.30 Cmol(+)/kg soil following the increase in time of contact from 30 to 120 days. However, this was in contrast to the results obtained from different MPR application rates. Under this aspect, exchangeable Ca increased steadily from 3.20 to 3.81 Cmol(+)/kg soil after applying 50 and 150 kg MPR-P/ha compared to 2.84 Cmol(+)/kg soil recorded in the control. The amounts of NH_4Ac-extractable Ca in the incubated soil to which Minjingu PR was added, increased significantly ($P \leq 0.05$) with application levels.

Table 5. Effect of MPR rates and MPR-Soil equilibration periods on exchangeable Ca (Cmol(+)/kg soil)

MPR rates (kg P/ha)	Equilibration period (Days)				Mean effects of MPR rates
	30	60	90	120	
0	2.912 i^{1}	2.919 i	2.847 ij	2.676 j	2.839 e^{1}
50	3.204 gh	3.227 fgh	3.174 h	3.185 gh	3.197 d
75	3.421 ef	3.40 efg	3.259 fgh	3.397 efg	3.369 c
100	3.647 bcd	3.562 cde	3.504 de	3.358 efgh	3.518 b
150	3.735 abc	3.769 ab	3.831 ab	3.887 a	3.805 a
Mean effects of equilibration periods	3.384 a^{2}	3.375 a	3.323 a	3.30 a	
LSD value	± 0.08428				
CV (%)	3.38				

LSD values for interaction (equilibration period × MPR rates) and that for MPR rates' effects are: 0.06583 and 0.09423, respectively.

1, 2 = all means followed by the same letter are not significantly different ($P \leq 0.05$) according to DNMRT.

Results from this study indicates that there were some dissolutions of dissolved MPR in the soil. Further, the released Ca ions from the dissolving MPR did not saturate the free protons in the soil to bring about the mass action reaction which would have decreased the dissolution. Therefore it suggests that there were still more chances for MPR to undergo further dissolution. The results of increase in exchangeable Ca with the increase of equilibration period and MPR rates in the present study were found to be in conformity with those observed by Ikkera (1986), Mnkeni *et al.* (1991). Ikkera (1986) observed that the increase in exchangeable Ca in the soil following the MPR being incubated for 60 days tended to decrease beyond the 60 days of incubation.

4.4 Correlation analyses done on some soil parameters after incubation periods

Table 6 depicts that there was a positive non significant correlation (r = 0.724) between soil pH and the amount of exchangeable Ca following their determination at the end of the incubation periods. This concurs with the fact that MPR like many other phosphate rocks are potential liming materials (Hellums *et al.*, 1989) since during their dissolution Ca is released as one of the dissolution products. Similarly, results from this study were found to show significant ($P < 0.001$) negative correlation between exchangeable Al and pH. Consistent with these findings, Hochman *et al.* (1992) reported a significant ($P < 0.01$) negative correlation between Al and pH in acidic soils. The simple correlation on some soil chemical properties (Table 6), showed that the exchangeable acidity was negatively and significantly correlated with available P (r = -0.908***) which is ascribed to a strong association of the two parameters. It could be argued that the increase in free Al ions in the soil tended to precipitate the released P from MPR into insoluble forms (Al-phosphates). A negative significant relationship (r = -0.902***) between the exchangeable Al and exchangeable Ca indicates that the soil acidity decreased as the exchangeable Ca concentration in soil-MPR incubated pots increased, and vice versa. Probably due to a slight liming effect following the exchange sites vacated by Al ions being virtually taken up by Calcium (Hochman *et al.*, 1992).

The positive correlation (r = 0.668***) between extractable P and soil pH, indicates that all these two parameters were liable to increase /decrease simultaneously as a result of Minjingu phosphate rock dissolution which also released P and Ca as two of its products [strongly related, (r = 0.893***)]. Some other soil properties, namely exchangeable acidity (r = - 9.08***) and exchangeable Al (r = - 0.855***), were strongly correlated with available P (Table 6). Such relationships confirm that the increase in H^+ and Al^+ in the soil renders P unavailable to crop plants through fixation at their exchange sites.

Table 6. Correlation analyses between some chemical properties of the soil after incubation times

	Exchangeable acidity	Exchangeable Al	Available P	Exchangeable Ca
pH (water)	- 0.754***	- 0.706***	0.668***	0.724
Exchangeable acidity			- 0.908***	
Exchangeable Al			- 0.855***	- 0.902***
Available P				0.893***

*** = highly significant (P < 0.001).

4.5 Dry matter yields of maize plants as effected by MPR-Soil equilibration periods and MPR rates

Table 7 depicts that incubation periods and MPR rates had an apparent effect on maize dry matter yields. The results revealed that, the increase in time of MPR–soil contacts reduced the dry matter yields. However, the MPR rates showed a general trend in increase of dry matter yields with respect to the increase in MPR applied levels.

Results have shown that when MPR was applied at planting time (zero day), the dry matter yields were surprisingly and significantly ($P < 0.05$) higher than when MPR was applied at 30, 60, 90 and 120 days before planting, respectively. These results could probably attributed to the immediate uptake of MPR released nutrients (mainly P and Ca) by the plants. Poor response of plants shown at the other incubation periods might have been due to poor root development during the early stages of plant growth following a high proportion of the P initially dissolved being rapidly retained by soil components (Di *et al.*, 1994a). However, it was also seen that maize plants responded to MPR applied rates significantly ($P < 0.05$) as Table 7 shows. Dry matter yields in MPR treated soils were relatively higher than those obtained from MPR untreated soils (controls). The highest level of Minjingu PR (150 kg P/ha) applied increased the dry matter yield approximately three times over that of control throughout the equilibration periods. At zero day (immediately following application of MPR), the highest MPR level of 150 kg P/ha was noted to bring about higher dry matter yields than the rest MPR levels applied, as regards to the interaction (equilibration periods × MPR rates) effects. This indicates that the soil was P deficient (Table 1). The overall increase in dry matter yields may partly be attributed to the increase in P and Ca uptake by the maize plants (Table 10 and 11).

The observed results of dry matter yield increase following the increase in MPR rates in the present study, somewhat reconciles with those obtained by Ikkera (1986), Mnkeni (1991) who worked on the same soil and found higher dry matter yields from MPR treated soils than from the controls. The improvement of crop response towards the applied MPR as compared with MPR untreated pots would be due to the availability of P released from the dissolving MPR. The results obtained from comparing the effect of incubation/equilibration periods were in agreement with those reported by Purnomo and Black (1994). The authors observed lower dry matter yields of wheat when North Carolina PR applied to a red podzolic (chromic luvisol) before planting time and this was attributed to the high soil P retention capacity which apparently reduced the initially available P from directly applied PR despite of the increase in PR with the soil P-sorption capacity (Chien *et al.*, 1990; Purnomo and Black, 1994). However, these results were in contrast to those reported by Paitnak *et al.*(1974) on rice grain yield.

Thus, results from the present study, probably elucidates that for better crop response, incorporation of MPR into the soil have to be done on the same day of planting, particularly for soils with high P fixing capacity, Oxic Haplustults inclusive (Chien *et al.*, 1990; Purnomo and Black, 1994). This would reduce the time of reaction between the PR released P and the soil constituents and might enable plant roots to compete with the soil P adsorption sites hence would become more available to plants.

Table 7. Effect of MPR rates and MPR - Soil equilibration periods on dry matter yields (g/pot) of maize plants

MPR rates (kg P/ha)	Equilibration period (Days)					Mean effects of MPR rates
	Zero	30	60	90	120	
0	5.12 hij[1]	4.20 ij	3.58 j	3.74 ij	3.78 ij	4.08d[1]
50	10.69 bc	7.15 efg	6.74 efgh	5.77 fghij	5.52 ghij	7.17 c
75	12.01 ab	7.92 defg	7.56 efgh	7.22 efgh	6.15 fghi	8.17 b
100	12.60 ab	8.85 cde	8.80 cde	7.76 efg	6.88 efgh	8.97 b
150	14.19 a	10.70 bc	10.24 bcd	8.73 cde	8.24 cdef	10.42 a
Mean effects of equilibration periods	10.92 a[2]	7.76 b	7.38 bc	6.64 cd	6.12 d	
LSD value	± 0.9623					
CV (%)	16.88					

LSD values for interaction (MPR rates × equilibration periods) and that for MPR rates are ± 2.152 and ± 0.9623, respectively.

1, 2 = all means followed by the same letter are not significantly different ($P < 0.05$) according to DNMRT.

4.6 The effect of Soil-MPR equilibration periods and MPR rates on P and Ca contents in maize plant shoots

4.6.1 P-content

Table 8 presents results of elemental P accumulation in plant shoots at different incubation/ equilibration period and MPR rate effects. The mean P accumulations in plant shoots ranged from about 0.22 to 0.30%, and from 0.19 to 0.26% following the incubation period and MPR rate effects, respectively.

Maize plants sown at the 60 days incubated soil were noted to have significant ($P < 0.05$) higher P contents as compared to those in 30, 90 and 120 days of incubation. This observation was probably associated with the corresponding high amount of dissolved P at 60 days of incubation (Table 2a and Table 2b) which consequently diffused into plants through root hairs. Similarly, the MPR applied rates significantly ($P < 0.05$) differed in influencing the P concentration in plant shoots whereby the highest P content was found in pots treated with 50 kg P/ha followed by 75, 100 and 150 kg P/ha in decreasing order. These kinds of results were found to be in contrast to the dry matter yield results noted in Table 7 above, as regards to the effect of MPR applied rates. It seems from these results that the decrease in P content in shoots resulted from the increase in dry matter yield with increasing MPR levels, hence attributing to the dry matter dilution effect.

However, the equilibration period × MPR rate interaction effects were also found to significantly influence the P concentration in plants and the highest interaction effect was observed when 100 kg P/ha was incubated for 60 days before planting (Table 8). Concluding from this observation of %P content increase in plant shoots harvested from soil-MPR incubated for 60 and 90 days relative to those at planting, 30 and 120 days of incubation, would similarly be attributed to their difference in dry matter yields, hence dry matter dilution. These observations may probably resulted from the decrease in P concentration in the soil solution surrounding the root hairs. Despite this, however, the change in the percent P in plant tissue may not be due to dilution of the plant P through increased growth, but might instead be the result of a decrease in the concentration of the P in the soil solution surrounding the roots. This has been found to be true especially if the P concentration in the soil solution was initially high enough to maintain the percent P in the plant above a minimum concentration of P (Kamprath and Watson, 1980).

On the other hand, the P concentration ranges in shoots were relatively below the critical ranges of 0.4 – 0.8 P% as suggested by Jones and Eck (1973) for maize plant (cut as whole plant above ground) grown for 30 to 45 days. Severe P deficient symptoms including purple coloration of the leaves and stems, drying and senescence of lower leaves were observed in the control pots and those which had relatively low rates of MPR (mostly pots with 50, 75 and 100 kg P/ha). P contents (%) were also noted to increase with incubation periods. This might have been consistent with the changes in P availability with incubation time and MPR levels applied (Table 2a and Table 2b). The undefined and inconsistent trends in the %P contents in the maize plants with incubation periods, needs to be researched upon further so as to explain the cause of the trends.

Table 8. Effect of MPR rates and MPR- Soil equilibration periods on P-contents (%) in maize plants

MPR rates (kg P/ha)	Equilibration periods (Days)					Mean effects of MPR rates
	Zero	30	60	90	120	
0	0.195 i^1	0.235 fghi	0.263 bcdefg	0.133 j	0.118 j	0.189 c^1
50	0.226 ghi	0.317 abcd	0.317 abcd	0.349 a	0.257 defgh	0.293 a
75	0.235 fghi	0.321 ab	0.334 a	0.324 a	0.244f ghi	0.291 a
100	0.224 ghi	0.224 ghi	0.3053 abcde	0.310 abcde	0.259 cdefgh	0.264 b
150	0.215 hi	0.199 hi	0.292 abcdef	0.319 abc	0.252 efghi	0.256 b
Mean effects of Equilibration periods	0.219 c^2	0.259 b	0.302a	0.287 a	0.226 c	
LSD value	0.2322					
CV (%)	12.58					

LSD values for the interaction (Equilibration period x MPR rates) effects and that for MPR-rates effects are: 0.05191 and 0.02322, respectively.

1, 2 = all means followed by the same letter are not significantly different ($P < 0.05$) according to DNMRT.

4.6.2 Ca content in maize plants

The effects of equilibration/ incubation periods and MPR rates on the Ca content (%) in maize plant shoots are summarised in Table 9. Ca content in plant shoots tended to increase with the increase in incubation period, but it decreased with increase in MPR levels.

The Ca concentrations differed significantly ($P \leq 0.05$) between different incubation periods. The average increase in Ca concentration followed the order: zero < 30 < 60 < 120 days. However, this trend was in contrast to the dry matter yield (Table 6), which might have contributed to the dilution of the Ca concentration in plant shoots (Maschner, 1990). However, Ca contents in maize plants were significantly higher ($P \leq 0.05$) in MPR untreated plants (control) than from MPR treated plants. The MPR at lowest rates found to have relatively higher Ca contents compared to higher rates (Table 9). The decline in Ca content in maize shoots following the increase in MPR rates, probably resulted from dilution effects arising from the increase in plant growth (Table 6).

However, Ca concentrations in this study were noted to be below the critical values range (0.9 - 1.6% Ca for the whole maize plant harvested 30 - 45 days after emergence) as previously established by Jones and Eck (1973). Based on these results it indicates that crop plants also suffered Ca deficiency. This was probably associated with the low amount of applied MPR and consequently a low amount of released Ca and the low Ca in the soil. The undefined trends in %Ca in the maize plants calls for more research and investigation.

Table 9. Effect of MPR-Soil equilibration periods and MPR rates on Ca-contents (%) in maize plant materials

MPR rates (kg P/ha)	Equilibration period (Days)					Mean effects of MPR rates
	Zero	30	60	90	120	
0	0.333 abcd^1	0.395 a	0.352 abc	0.369 ab	0.390 a	0.368 a^2
50	0.250 e	0.270 de	0.250 e	0.282 cde	0.331 abcd	0.277 b
75	0.223 e	0.216 e	0.235 e	0.230 e	0.289 cde	0.239 c
100	0.229 e	0.256 de	0.298 bcde	0.255 de	0.255 de	0.259 bc
150	0.241 e	0.253 de	0.247 e	0.259 de	0.266 de	0.253 bc
Mean effects of equilibration periods	0.255 b^1	0.278 ab	0.276 ab	0.279 ab	0.306 a	

LSD value (P = 0.01) 0.03097

CV (%) 12.66

LSD values for interaction (Equilibration period × MPR rates) effects and that for MPR-rates' effects are: 0.06925 (P = 0.01) and 0.02322 (P = 0.05).

1, 2 = all means followed by the same letter are not significantly different (at $P \leq 0.05$, respectively) according to DNMRT.

4.7 Plant P and Ca uptakes as influenced by soil - MPR equilibration period and MPR rates

4.7.1 Plant P - uptake

The results in Table 10 show the comparison of MPR-Soil incubation periods and MPR rates effects on the P uptake. The P uptake by plants was noted to increase with the decrease in incubation/equilibration time, while it tended to increase with increase of the MPR rates, though it did not reach the optimum level. With application of MPR at sowing time (zero day) or at 60 days prior to sowing, the crop recovery of fertilizer P was found to be significantly higher ($P < 0.05$) than from any other pots. For example, the mean P uptake was 23.64 mg/pot in plants grown at zero incubated/equilibrated soils, while it was 22.40 mg/pot for plants harvested from 60 days incubated soils. The plant uptake was also found to be positively and significantly related ($r = 0.551$) with P content (%P) at $P < 0.001$. The increased P uptake for the zero time incubated soils might probably have been attributed to the reduced time for P immobilization/ adsorption, thus increased chances for an immediate and rapid uptake of P released from the MPR. It might have been also contributed by the pH related changes in the rhizosphere, influencing P dissolution from sparingly soluble sources (Nye and Kirk, 1987).

Statistically, the P uptake responses were also found to be significantly influenced by MPR rates ($P < 0.05$). The P recovered by maize plants grown in the MPR treated pots were relatively higher than those recorded in the control pots (Table 10). That is at 150 kg P/ha resulted in 26.29 mg P/pot uptake as compared to only 7.50 mg P/pot when no MPR was applied. The key reason for increased P uptake is presumably associated with the response to extra P released from MPR dissolution as it was subsequently effected by MPR levels (Table 2a and Table 2b). These results were in agreement with those reported by Ikkera (1986) and Mnkeni *et al.* (1991). Mnkeni *et al.* (1991) found that MPR at 80 kg P/ha application rate significantly increased maize P uptake in Magadu (Haplustult) and Mzumbe (Haplustox) soils. The low pH values (< 5.2) and low P content (< 6.5 ppm) for both soils was given as explanation for effecting a considerable dissolution of MPR in these soils which subsequently led into an increased P uptake by maize. Results from the present study, indicates that MPR can serve as an alternative source of P in acid soils like the Oxic Haplustults which are low in available P and can be directly applied to supply P for maize plants. This could be achieved through referring to most appropriate period(s) for MPR/ PRs application into these particular soils with high P sorption capacity.

Table 10. Effect of MPR-Soil equilibration periods and MPR rates on P-uptake (mg/pot) by the maize plants

MPR rates (kg P/ha)	Equilibration periods (Days)					Mean effects of MPR rates
	Zero	30	60	90	120	
0	9.99 ij^{1}	9.85 ij	9.43 ij	4.96 jk	3.26 k	7.50 d^{1}
50	24.03 bcde	22.56 cdef	20.95 def	20.36 efg	14.19 hi	20.42 c
75	28.17 abc	32.13 a	24.84 bcde	22.77 cdef	15.01 ghi	24.58 ab
100	28.29 abc	19.74 efgh	26.85 abcd	23.85 bcde	17.67 fgh	23.28 b
150	27.71 abc	25.61 bcde	29.93 ab	27.44 abc	20.76 defg	26.29 a
Mean effects of equilibration periods	23.64 a^{2}	21.98 b	22.40 a	19.87 b	14.18 c	
LSD value	2.342					
CV (%)	15.62					

LSD values for interaction between equilibration periods and MPR rates, and MPR rates are: 5.236 and 2.342, respectively.

1, 2 = all means followed by the same letter are not significantly different ($P < 0.05$) according to DNMRT.

4.7.2 Plant Ca – uptake

The effects of equilibration periods and MPR application rates are presented in Table 11. The Ca uptake by maize plants generally tended to decrease with the increase in soil - MPR contact periods whereas in contrast increased with the increase in MPR application rates/ amounts into soils. At zero day the mean uptake was 26.70 mg Ca/pot compared to 17.88 mg Ca/pot of which was noted from plants raised in 120 days of soil-MPR incubation pots.

Longer soil-MPR incubation periods tended to reduce the Ca uptake by maize plants significantly ($P < 0.05$) which might have been enhanced by the increase in KCl – extractable Al (Appendix 1). However, increasing amounts of MPR applied into the soil significantly ($P < 0.05$) increased maize Ca uptake for all incubation periods. When the rates of fertiliser MPR were doubled and tripled the relative increases of plant Ca contents were approximately 2 and 3 times higher, respectively, than the lowest rate (50 kg P/ha). This study signifies that there was a positive crop response towards the increase in MPR applications. These results are to a large extent inconsistent with the Ca concentration (%) in the maize shoots (Table 9).

On the other hand, results from the present study were found to be in line with that reported Mnkeni *et al.* (1991) on the increase in Ca uptake with respect to MPR rates increase in Haplustults and Haplustoxs. It was concluded that the observed increase in extractable Ca levels due to MPR application depicted a further evidence on considerable dissolution of MPR in these soils.

Table 11. Effect of MPR-Soil equilibration periods and MPR rates on Ca-uptake (mg/pot) by maize plants

MPR rates (kg P/ha)	Equilibration periods (Days)					Mean effects of MPR rates
	Zero	30	60	90	120	
0	17.05 defghi^1	16.49 fghi	12.57 I	13.86 hi	14.78 ghi	14.95 d^1
50	26.67 bc	19.27 defgh	16.94 efghi	16.49 fghi	18.29 defgh	19.53 c
75	26.71 bc	21.84 cdef	17.31 defghi	16.44 fghi	17.40 defghi	19.94 c
100	28.76 b	22.55cd	26.19 bc	19.74 defg	17.14 defghi	22.87 b
150	34.31 a	27.04 bc	25.33 bc	22.49 cde	21.78 cdef	26.19 a
Mean effects of equilibration periods	26.70 a^2	21.44 b	19.67 bc	17.80 c	17.88 c	
LSD value	± 2.106					

CV (%) 13.86

LSD values for interaction (Equilibration periods × MPR rates) effects and MPR rates are: 4.710 and 2.106, respectively.

1, 2 = all means followed by the same letter are not significantly different ($P < 0.05$) according to DNMRT.

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Table 11. Effect of MPR-Soil equilibration periods and MPR rates on Ca-uptake (mg/pot) by maize plants

MPR rates (kg P/ha)	Equilibration periods (Days)					Mean effects of MPR rates
	Zero	30	60	90	120	
0	17.05 defghi[1]	16.49 fghi	12.57 I	13.86 hi	14.78 ghi	14.95 d[1]
50	26.67 bc	19.27 defgh	16.94 efghi	16.49 fghi	18.29 defgh	19.53 c
75	26.71 bc	21.84 cdef	17.31 defghi	16.44 fghi	17.40 defghi	19.94 c
100	28.76 b	22.55cd	26.19 bc	19.74 defg	17.14 defghi	22.87 b
150	34.31 a	27.04 bc	25.33 bc	22.49 cde	21.78 cdef	26.19 a
Mean effects of equilibration periods	26.70 a[2]	21.44 b	19.67 bc	17.80 c	17.88 c	
LSD value	± 2.106					

CV (%) 13.86

LSD values for interaction (Equilibration periods × MPR rates) effects and MPR rates are: 4.710 and 2.106, respectively.

1, 2 = all means followed by the same letter are not significantly different ($P < 0.05$) according to DNMRT.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the results from this study, it could be concluded that the Oxic Haplustults has low amount of Bray-1-P, low exchangeable Ca, low pH (very strong acid reaction) and a low CEC. This implies that the Oxic Haplustults has high P fixing capacity and a significant sink for Ca and P, hence it is of low fertility status.

Based on the glasshouse pot experiment results, Bray-1-P increased with increasing rates of MPR applied to the soil. Despite significant increase in MPR-P in the soil, still the maximum/ optimal P was not attained. This implies that the highest rate applied was not sufficient to saturate the soil P-fixation/ adsorption capacity. On the other hand, the amount of P released increased with time of incubation/equilibration up to about 75 days and decreased thereafter probably following its reaction with Al and Fe hydrous oxides forming Al and Fe phosphates.

The soil pH increased with increasing MPR application rate, but decreased with increasing incubation period, particularly after about 75 days of incubation. Similarly the extractable Ca tended to increase with MPR rate, and slightly decreased with increase in the incubation period. These results indicates that MPR dissolution releases Ca^{2+} and OH^-, as two of the constituent components of MPR, which subsequently reacted with the soil protons to increase the pH value of the soil in question.

Both exchangeable acidity and exchangeable Al tended to decrease with increasing rate of MPR, and also increased with increasing incubation period. The possible conclusion from this observation is the release of Ca from $CaCO_3$ of the MPR that influenced the $Al\text{-}O^{-1}$ binding sites hence reducing the released protons from the exchange sites. This implies that MPR could be referred to as a potential liming material when applied to acidic soils like the Oxic Haplustults.

Dry matter yields increased with increasing MPR rates and this trend was noted to be consistent with the release of P and Ca from the MPR application rates. These results indicated that the maize plants responded positively to the MPR applications. The dry matter yields were more pronounced at zero time of incubation, then decreased at a decreasing rate with increasing period of incubation. This was possibly associated with the immediate uptake and assimilation of nutrients (mostly P and Ca) released from the dissolving MPR. The decrease in dry matter yields with increase in soil-MPR contact period, suggests that the P released was rendered unavailable to plants following the formation of insoluble Al and Fe phosphate compounds, coupled with poor plants root growth as due to increased soil compaction with increasing incubation periods.

The %P and %Ca in plant shoots, relatively decreased with increasing MPR rates in contrast to the dry matter yields. It is probable that the increase in plant growth with the increase in MPR rates led into the dilution of P and Ca concentrations in plant shoots. The P and Ca contents in the maize plants were below the critical levels (Jones and Eck,

1973) hence the amount of MPR applied was below the required level to release sufficient amounts of P and Ca to the maize plants. It could therefore be concluded that MPR rates should be increased to about four times that it is to 600 kg P/ha as MPR.

5.2 Recommendations

The same study has to be conducted under field conditions, where direct phosphate rock applications has to be well integrated with other agronomic practices to capitalize on its agronomic effectiveness. The appropriate alternatives might be: the broadcasting and banding of the MPR so as to come out with a realistic rate of MPR for the Oxic Haplustults. MPR should be applied at planting time in soils that are strongly acid and with very low levels of Bray-1-P and exchangeable Ca. Adoption of this procedure will reduce the chances for reversible fixation of the initially released MPR-P by reactive Al and Fe compounds in the soil.

Other essential plant nutrients like sulphur, zinc just to mention a few should be applied to the soil (Oxic Haplustults) in order to enhance better crop response to the MPR. Organic manures and crop residues should to be incorporated into the soil (Oxic Haplustults) to increase the MPR dissolution, CEC, improve the water holding capacity and structure of the soils.

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APPENDICES

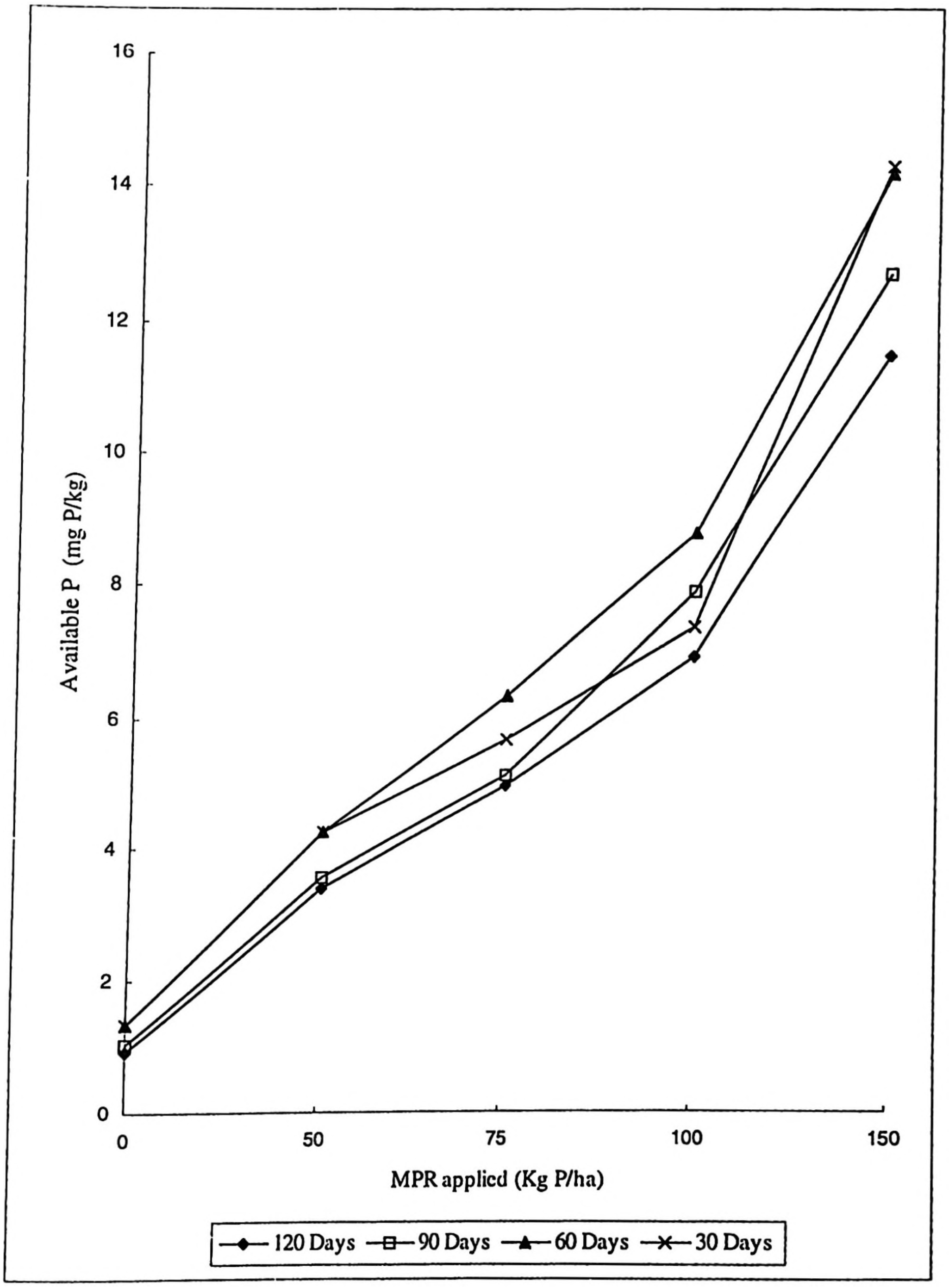
Appendix 1. The effect of MPR-Soil equilibration periods and MPR rates on exchangeable Al (Cmol(+)/kg soil)

MPR rates applied (kg P/ha)	Equilibration periods (Days)				Mean effects of MPR rates
	30	60	90	120	
0	1.170 a[1]	1.104 ab	1.203 a	1.175 a	1.163 a[1]
50	0.935 cd	0.956 cd	0.963 cd	1.015 bc	0.967 b
75	0.776 efg	0.864 de	0.831 def	0.838 def	0.827 c
100	0.717 fgh	0.726 efgh	0.705 fghi	0.730 efgh	0.720 d
150	0.594 hi	0.645 ghi	0.703 fghi	0.570 i	0.628 e
Mean effects of equilibration periods	0.839 a[2]	0.859 a	0.881 a	0.866 a	
LSD value	± 0.05726				
CV (%)	9.06				

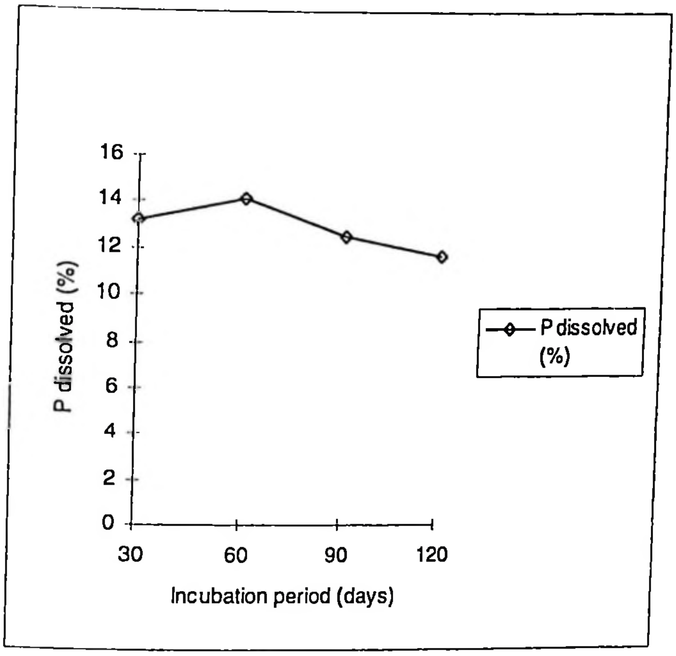
LSD values for interaction (incubation periods x MPR rates) means and that for MPR rates effect means are: ± 0.0.4472 and ± 0.06402

1, 2 = all means followed by the same letter do not differ significantly (P = 0.05) according to DNMRT.

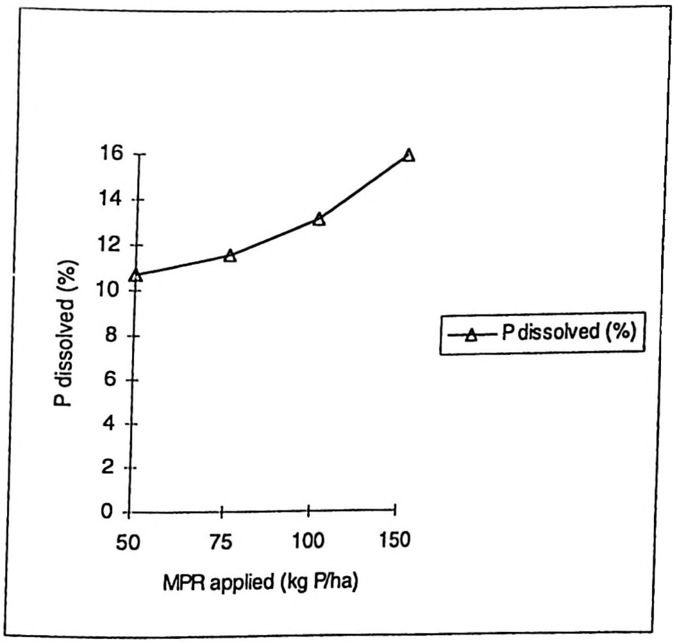
Appendix 2. Minjingu Phosphate Rock dissolution at different soil - MPR equilibration periods and MPR rates



Appendix 3a. The effect of incubation periods on MPR dissolution.



Appendix 3b. The effect of MPR rates on MPR dissolution



Appendix 4a. Soil physical properties of the Oxic Haplustults profile.

Soil sample and depth cm	Munsell soil colour notation		% Particle size distribution			Bulk density g/cc	Water between 33 1500 kPA
	Moist	Dry	Sand	Silt	Clay		
Pedon 1:							
Ap 0-11	7.5YR 4/4	7.5YR 5/4	53	3.5	43.5	1.4	10.5
B21t 11-36	5YR 4/8	5YR 5/8	33.3	3.5	63.2	1.6	10.7
B22t 36-82	5YR 5/8	5YR 6/8	30.3	3.5	66.2	1.6	14.4
B23t 82-152+	5YR 5/8	5YR 6/8	27.2	4.8	68.0	1.6	14.4

Source: Kaaya *et al.* (1994).

Appendix 4b. Soil chemical properties of the Oxic Haplustults profile.

		pH	pH	P	C	N	Ca	Mg	K	Na	NH_4OAc CEC	BS
Soil sample	depth (cm)	H_2O	$CaCl_2$	mg/kg	%	%	me/100g soil				me/100g soil	%
Pedon 1:												
Ap	0-11	5.8	4.5	1.3	1.1	0.21	1.70	0.86	0.90	0.08	13.72	25.8
B21t	11-36	5.3	4.3	1.3	0.7	0.11	1.12	0.58	0.35	0.15	16.66	13.2
B22t	36-82	5.3	4.3	1.4	0.5	0.08	0.47	0.66	0.10	0.08	17.64	7.4
B23t	82-152+	5.3	4.2	1.1	0.3	0.05	0.70	1.36	0.09	0.27	15.68	15.4

Source: Kaaya *et al.* (1994).