PHOSPHORUS AVAILABILITY AND CARROT GROWTH AS INFLUENCED BY PHOSPHATE ROCK MANAGEMENT UNDER ACID SOILS IN MURANG'A AND THARAKA NITHI COUNTIES

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Phosphorus availability and carrot growth as influenced by phosphate rock management under acid soils in Murang'a and Tharaka Nithi Counties

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A thesis submitted in partial fulfilment of the Requirements for the degree of Master of Science in Horticulture of the Jomo Kenyatta University of Agriculture and Technology

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university.

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DEDICATION

This work is dedicated to The Mwangi's family for their unwavering support and love throughout the study.

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LIST OF ABBREVIATIONS/ACRONYMS

AAS	Atomic Absorption Spectrophotometer
ANOVA	Analysis of Variance
ATP	Adenosine Triphosphate
CEC	Cation Exchange Capacity
COOH	Carboxyl group
DAS	Days after Sowing
DNA	Deoxyribonucleic acid
DPR	Dissolved Phosphate rock
EDTA	Ethylenediaminetetraacetic acid
ICIPE	International Centre for Insect Physiology and Ecology
JKUAT	Jomo Kenyatta University of Agriculture and Technology
KALRO	Kenya Agriculture and Livestock Research Organization
LR	Long rain
LTE	Long Term Experiment
MPR	Minjingu Phosphate rock
NPK	Nitrogen, Phosphorus, Potassium
P	Phosphorus
PRE	Phosphorus Recovery Efficiency
PPR	Powdered Phosphate rock

PSB	Phosphorus Solubilizing Bacteria
PUE	Phosphorus Use Efficiency
RNA	Ribonucleic acid
PR	Phosphate rock
RV	Rift Valley
SOC	Soil Organic Carbon
SPR	Standard Phosphorus Requirement
SR	Short Rain
SSA	Sub-Saharan Africa
TSP	Triple Superphosphate
USD	United States Dollar

ABSTRACT

Soils from Central Highlands of Kenya are characterized by low phosphorus (P) availability with crops exhibiting P deficiency symptoms. The objective was therefore to determine the P sorption characteristics of the soils and to assess their standard P requirements in order to recommend the P fertilizer required for different crops in the area. Besides, the study aimed at assessing the efficiency of lemon and pineapple juices and the concentration and time needed to release more than 50% of available P from phosphate rock (PR), and; the effect of different types of PR management on carrot yields, nutrient uptake, and P-use efficiency. In the first study, four different soils (Humic andosols, Orthic acrisols, Humic nitisols and Rhodic nitisols) from the Central Highlands of Kenya were used for the study. Phosphorus sorption was determined using the Batch Equilibrium method, data fitted in the Langmuir isotherm model and relationships between the P adsorption maximum (Smax) and soil properties determined by simple regression. The standard phosphorus requirement (SPR) of the soils was determined from P sorption curves at soil solutions of 0.05 to 0.2 mg L^{-1}. About 46 to 81% of P added to the soils was adsorbed. The sorption maxima (Smax) of P were similar for the Humic andosols and Humic nitisols and were significantly higher than in Rhodic nitisols and Orthic acrisols. Gibbsite, kaolinite, calcium and iron were identified as the main factors influencing Smax in the soils. In the second and third experiments, a laboratory incubation trial to assess efficiency of organic juices to solubilize PR and field trials to assess efficiency of dissolved PR on crop growth and yield were set up at two sites with Humic Andosols and Orthic Acrisols over two seasons in Kenya. Lemon and pineapple juice and distilled water at volumes 100, 200, 300, 400 and 500 mLs were used in dissolution of 100 g of PR. In a Randomized Complete Block Design, replicated three times, eight treatments were compared. Lemon juice was effective in solubilizing PR, releasing 63% of the total P applied into available P, compared to 11% for pineapple juice and 6% for water. The combined application of compost and PR dissolved in lemon juice at planting significantly increased P and K uptake, P use efficiency and carrot yields which was comparable to the use of triple superphosphate and compost. Soils from Murang'a and Tharaka Nithi counties in the central highlands of Kenya fixed large amounts of phosphorus and interventions will be required to reduce phosphorus fixation and enhance its availability to crops. However, the differences in soils' phosphorus fixing capacity and their standard phosphorus requirement indicate that policy interventions should be soil specific. The study concludes that the dissolution of phosphate rock with lemon juice at a ratio of 1:5 phosphate rock to lemon juice and its combined application (immediately after dissolution) with compost at planting improves nutrient uptake, phosphorus use efficiency and crop yields. It is recommended that further studies be done to explore the possibility of using citrus peels or other acidic organic materials to enhance the solubility of phosphate rock, and to assess their practical feasibility and the economic advantage(s) in the large scale production of high value crops.

CHAPTER ONE

INTRODUCTION

1.1 Background information

Phosphorus is one of the essential macro-elements required by the plants for growth and development (Abdissa et al., 2011). Adequate supply of P in plants is important in encouraging vigorous shoot and root growth, promoting early maturity, increasing water use efficiency and improving grain yield. In most tropical soils, P availability is limited for plant uptake by binding to the Aluminum (Al), Iron (Fe) in low pH soils and Calcium (Ca) ions in soils with high pH. Most highland soils such as the Acrisols, Andosols and Nitisols are characterized by a pH lower than 5.5. These soils have high Al and Fe ions that bind strongly to the applied P to form Aluminum and Iron phosphates complexes. This reduces the efficiency of chemically processed P fertilizers in soil by binding more than 80% of applied P hence unavailable to plants (Balemi and Negisho, 2012). There have been attempts to utilize cheap alternatives of P such as reactive low grade phosphate rock (PR) materials. Application of large amounts of PR at one time has been shown to improve P status of soil and to have a positive residual effect on yield of crops for continuous cropping seasons (Adamtey et al., 2016). However, due to low solubility of PR when directly applied to soil, P uptake by plants is limited. This requires solubilization of PR before application to crops to enhance immediate P uptake and use for the current crop.

Several studies have been done on solubilization of PR for utilization in acidic soils. These include dissolution by microorganisms such as bacteria and fungi (Abbasi et al., 2015, Mukhongo et al., 2016); incorporation in manure and composts (Nishanth and Biswas, 2008; Zafar et al., 2017) and milk sludge (Andres et al., 2016). The microorganisms, composts, manure and milk sludge solubilize P by production of organic acids such as citric and malic acids that solubilize P through proton extrusion, and chelating substances that substitute Ca^{2+} and Mg^{2+} ions in PR to release P in orthophosphate (H_2PO^{4-}) form which is available to plants (Osman, 2015). However, even with the above ways to improve efficiency of PR, the use efficiency of P by crops remains low at less than 30% (Zafar et al., 2017). There is limited information on utilization of locally available organic materials in dissolution of PR. Lemon juice contains high amount of organic acids (e.g. citric and malic acids) 77.83 g L^{-1} with a concentration of citric acid of around 73.94 g L^{-1} (Nour et al., 2010). On the other hand pineapple juice contains 5.09 g L^{-1} organic acids (citric and malic acids) with citric acid concentration of around 3.26 g L^{-1} (Xin-Hua et al., 2014). High amount of hydrogen molecules in the citric acid enhances mobilization of P molecules from PR. The study therefore sought to assess fixation capacity of soils in the Central highlands of Kenya and evaluate the efficiency of organic fruit juices in improving P release in PR and P use efficiency of crops grown in the soils.

Nutrient availability through incorporation of crop residues, management of organic soil amendments contributes to sustainable production of vegetable crops. According to Adamtey et al. (2016), crops deplete available nutrients such as phosphorus during their growth cycles requiring continuous addition of phosphate fertilizers and enhancement of nutrient release through incorporation of soil organic matter. Carrot has been identified as a crop of high economic importance in the central highlands of Kenya due to its marketability and high nutrition value (Grubben and Denton, 2004). Production is however relatively lower compared to potential production levels. Carrot plant has been demonstrated as a moderate feeder of nutrient fertilizers (Mbatha *et al.*, 2014). Phosphorus is an important element in carrot for the root elongation and expansion and leaves growth (Nahar *et al.*, 2014). Deficiency of P in carrots leads to reduced carrot roots that are dwarfed and thin decreasing the yields and the older leaves develop a strong purple coloration and die early (Fageria *et al.*, 2013). The plant has a taproot system with numerous number of root hairs that increase P uptake. Determination of phosphorus use efficiency (PUE) in the current study was important in enabling development of recommendations on best management practices of PR that leads to high P uptake and utilization in comparison to use of mineral fertilizer and better understand the PUE of carrot vegetable crop.

1.2 Statement of problem

Adequate P fertilization to plants is important for faster and optimum plant growth and yields. However, availability of P to plants is strongly influenced by the binding effects of the aluminum and iron ions in acidic soils and calcium and magnesium in alkaline soils. This results in about 46 to 80% of the P applied to be locked becoming unavailable for plant uptake resulting in P deficiencies. High sorption results in P deficiency symptoms in crops at early to mid-crop growth stages especially in organic farming. To meet plant's P demand, farmers apply fertilizers such as triple superphosphate (TSP) or phosphate rock, animal manure and composts prepared from animal dung and plant residues (Akande et al., 2008). Most small scale farmers in Sub-Saharan Africa especially in central highlands of Kenya face challenges in meeting P requirements of crops due to high unavailability and cost associated with use of mineral fertilizers. This results in low crop yield, food insecurity and low income. Carrot are among the high value vegetable crops in the central highlands of Kenya, but its production has been constrained by poor nutrition. This has resulted in farmers experiencing yields that are far below the potential levels reducing the income earned.

Phosphate rock is an alternative source of P fertilizer especially in organic farming systems. However, its effectiveness for plant fertilization through direct application is limited due to low solubility and release of water soluble P (Ahmat et al., 2014). This prevents its efficiency for direct application in providing P for plants especially the short seasoned crops in organic farming systems (Chien, et al., 2010). Various interventions have been studied to increase availability of P from PR. These interventions include a combined application with compost or manure (Zafar et al., 2017), solubilization with industrial organic acids (Wahba et al., 2018), milk sludges (Andres et al., 2016) and P solubilizing microorganisms such as bacteria and fungi (Abbasi et al., 2015). However, P recovery efficiency with these approaches is still low (18-29%) (Zafar et al., 2017). Farmers further lack access, knowledge and skills to P solubilizing bacteria and fungi

(Mukhongo et al., 2016). Suitable ratio of PR to milk sludge concentration and time of solubilization of PR for effective P recovery and utilization is also limited.

With these problems at hand, it is important to investigate the P sorption characteristics of soils of central highlands of Kenya to understand the specific amounts of P adsorbed, factors responsible for sorption and standard P requirements of these soils. Low molecular organic acids has been used to solubilize PR but information on the use of organic acids from locally available materials and their suitable ratio with PR, optimum dissolution time and their efficiency in P recovery is limited. The study aimed at establishing effective means of P release from PR through solubilization with fruit juices that contain high amount of organic acids hence increasing the availability of P in the compost mixed with PR and the PR applied to the crops. In addition, the study also aimed at establishing the most effective management of compost and PR that has the most benefits in terms of high P availability in the soils improving the growth and yield of the carrot crop. Compost manure is essential in organic farming and specifically to the study as it adds organic matter to the soil that binds the mineral adsorption sites of phosphate ions making P available to plants.

1.3 Justification

All crops require P for their growth and reproduction. Deficiency of P in food crops leads to poor growth and yielding causing reduced food production. Most of the agricultural productive land in Kenya is covered by the acidic soils that deprive the crops of P nutrient as it is bound tightly to the colloids (Ahmat et al., 2014). Degradation of the soil systems is intense implying that most of these essential nutrients like P are not available to the crops (Balemi and Negisho, 2012). High P sorption in acidic soils results in very little amount of P that is available for plant utilization. Farmers face problems in ensuring sustainable fertilization of crops due to relatively high cost and limited access of P fertilizers. There is a need to sustainably intensify agricultural production systems in order to enhance productivity, food security and incomes. In this context, it is paramount to develop novel, soil-specific technologies, pilot test and transfer them to farmers in a relatively short time. Phosphate rock, an affordable source of organic P is capable of supplying plants with adequate P for optimal growth and yield (Okalebo et al., 2007). However due to low solubility of PR in soil to release P, there is need to develop methods in which P solubilization can be enhanced using locally available sources of organic juices providing an alternative to use of inorganic acids for the organic farming systems. This points to the need to find better ways to manage PR to enhance P availability to plants and increase agricultural productivity.

1.4 Main objective

To assess the sorption capacity of P in acidic soils and investigate ways of improving P availability from PR for plant uptake and utilization.

1.5 Specific objectives

1. To determine the extent to which P is sorbed by the different soils of central highlands of Kenya
2. To assess the efficiency of acidic juices and volumes used in the dissolution of phosphate rock.
3. To assess the effects of combining and composting of phosphate rock and organic residues on crop growth, root development and crop P use efficiency.

1.6 Hypotheses

1. Acidic soils of central highlands of Kenya have low fixing capacity of P added.
2. Type of organic acids (e.g pineapple and citrus juices) and volume used do not differ in their effect on PR dissolution.
3. Composted phosphate rock and organic residues and their combinations will not enhance crop growth, root development and crop P use efficiency.

CHAPTER TWO

LITERATURE REVIEW

2.1 Carrot crop

2.1.1 Origin

Carrots (*Daucus carota*) belong to the family Apiaceae (Umbelliiferae). The crop is believed to have originated from Afghanistan and spread all across the world (Zyskowky et al., 2010). It is well known for its taste, fibre, beta and alpha carotenes which are components of vitamin A to human (Ojowi, 2013).

2.1.2 Economic and ecological importance

Carrots are mainly cultivated for their roots that are consumed raw as salad or cooked as vegetables. In Kenya, carrot is an important crop grown for both domestic and export market with about 5504 hectare of land cultivated and 179844 metric tons produced (Ministry of Agriculture Livestock and Fisheries, 2015). It is an increasingly valued crop for small-scale farmers in central highlands of Kenya due to its marketability, short maturity period and low attention required to manage it (Grubben and Denton, 2004). The common varieties produced by farmers are Nantes, Oxheart and Chantney, although farmers prefer the Nantes variety due to its sweet taste and deep orange colour that is preferable in the market. Besides, carrot takes about 100 days to mature and produces about 14 to 17 tonnes per acre. The crop is ideal to the farmers as it produces well in all seasons meaning that farmers grow carrot throughout the year resulting in regular flow of income to the farmers.

2.1.3 Nutrient requirement

The plant is a moderate feeder and requires moderate application of nutrients to produce optimum compared to other vegetables such as the alliums (Mbatha et al., 2014). In Kenya carrot production requires about 40.15 kg ha^{-1} P applied during planting and top dressed with 52 kg ha^{-1} N for optimal growth (Grubben and Denton, 2004, Ministry of Agriculture, 2002). Nitrogen and phosphorus fertilizer application is important in increasing the root length and diameter, leaf growth and reducing branching (Nahar et al., 2014). Application of organic materials in the land before planting is highly recommended for carrot production (Mbatha et al., 2014). Organic materials add microorganisms that enhance availability of the nutrients to the crop and lowers soil bulk density enhancing root penetration. This crop is of importance in our study as the assessment of root shape, length and biomass will give us an insight of how the available form of P was obtained and utilized by the plant.

2.2 Phosphorus availability in soils

Phosphorus is an essential element in all living cells of plants involved in many physiological and biochemical processes (Sekhar et al., 2008). Phosphorus is a component of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) structures which are holding and translating sites for genetic information. Its deficiency leads to plants having poor growth and development, low yields, delayed ripening and low quality of harvestable crop parts such as seeds. When plants die and decay, phosphorus is taken back to the soil in form of organic phosphorus. Different forms of P are available in soil (Costa et al., 2016). These soil P categories are: labile P which is the inorganic P held weakly in the Al and Fe oxides of the clay minerals and found in the solution; moderately labile P, which is the inorganic and organic forms of P held more strongly in the Al and Fe oxides by chemisorption; and non-labile P, which is the insoluble form of P held strongly within the Al and Fe oxides surfaces of soil aggregates and held in Ca or apatite minerals and more weathered soils (Costa et al., 2016). Labile P is the most available form of P that is taken up by the plants, easily leached and highly fixed in soil colloids.

2.3 Phosphate rock

Phosphate rock (PR) is the main source of elemental P and a raw material for inorganic P fertilizers production (Zapata and Roy, 2004). It is applied directly to the soil or solubilized first to improve P availability to crops. Efficiency of PR in making P available to crops is dependent on soil properties, type of the rock, climatic conditions, cropping system and management practices of the nutrients. Solubility of PR is regarded to be high in low pH, and soils with high cation exchange capacity, relatively high organic matter and low calcium and phosphate ions. In addition, aggregate size of PR influences the rate of solubilization with finely ground PR dissolving at a faster rate compared to PR with large particle size (Msolla et al., 2005; Chien et al., 2010). Ways to improve P availability from PR has been studied extensively.

2.4 Direct application of phosphate rock for crop production

In most developing countries that have adequate PR resources, direct application of PR has been employed to intensify agriculture. Soils with high acidity, high cation exchange capacity, high organic matter, and low calcium and phosphate levels in soil solution respond more favourably to direct PR application. In most tropical and subtropical soils with pH less than 5.5, with high P binding capacity, direct PR is recommended. Gweyi-Onyango et al. (2010) investigated the efficacy of PR directly applied to tomato plants in acidic Ferralsols and Luvisols of Maseno and Kibwezi regions of Kenya. The study found that positive response to tomato growth was achieved in acidic Ferrasols as opposed to Luvisols increasing the root and shoot biomass of tomatoes grown in Maseno. The author attributed this response to reduction of aluminium toxicity in the Ferrasols improving P availability. Similarly, Nyambati and Opala (2014), studied the effect of Minjingu PR and TSP on maize growth and yield in the Acrisols and Ferralsols of Khwisero and Nyabeda region respectively in Kenya. A high relative agronomic effectiveness of MPR was obtained in Khwisero (112%) and Nyabeda (83%) hence concluding that direct application of PR was suitable in the region. However, positive effect of PR applied directly is less profound in short seasoned crops especially during the first year of application. The apatite form of P in PR is water insoluble reducing the amount of P released for plant uptake. There are various considerations that must be made when applying PR directly to ensure there is a direct product benefit. First, it is rational to consider conducting a cost-effect analysis. This enables one to have a proper understanding of the effects that direct PR have on plants and whether the impacts are sustainable. This ensures that the determination of the uptake of phosphorous will have the expected benefits with limited impacts that outcast the benefits obtained. According to International Institute of Tropical Agriculture (2010), PR powder would mean using PR as a direct resource that is vulnerable to being utilized by physical extraction for use in different other soil farms. This may end up changing the soil structure of the source and thus rendering the entire utility unsustainable. It is important that farmers are involved in a well-guided Decision Support System (DSS), which provides necessary information on important decisions such as the application of PR powder in farms. This information is important since there are different considerations that have to be determined to enable optimum productivity. First, the soil pH has to be determined since it determines the solubility of the PR powder and thus its effectiveness. Besides, Shukla (2013) reported that the availability of microbial organisms is also important information as it will ensure the availability of P-solubilizers for plant uptake of P. The information also ensures that proper P to PR ratio can be determined for best productivity results.

2.5 Management of phosphate rock to enhance phosphorus availability

2.5.1 Dissolution of phosphate rock with organic acids

Several studies have identified different possible ways to increase P availability from PR. Manure, composts, sludge and laboratory organic acids have been tested and shown to effectively enhance P release from phosphate rock (Singh and Amberger, 1997; Akande et al., 2008; Nishanth and Biswas, 2008; and Agyarko et al., 2016). This is usually conducted with the help of organic acids that include oxalic, gluconic, fulvic and citric acids. During this entire process, there is a chemical reaction that takes place that involves optimization of the availability of P. In this case, the dissolution of the P in the organic acids depends on the nature and type of phosphates in PR. This is because the number of acidic protons generated biochemically together with the dissociation of the acid is constant. The rate of dissolution is changed by decreasing the solution pH; this contributes to the surfacing of the mineral cations through complex formation (Vine, 2012). This affects the saturation point of the solution that affects the solution speciation of aluminum ions. This entire dissolution process is an indication that the protons of organic acids are generated through a biochemical process to enable dissociation. With the availability of hydrogen ions (H^+) organic juice solution and PR, the dissolution of PR is influenced greatly since the solution is highly dependent on the dissociation constant of the acid (pKa) (Shukla, 2013). Through this consideration, it is possible that there is a high level of dissolution that takes place since citric acid is involved. Primarily, citric acid contains the highest dissociation constant (pKa = 4.13). Therefore, there is more P extraction from PR by citric acid compared to gluconic and oxalic acids that have pKa 3.6 and pKa 1.06 dissolution constant respectively. This generally means that there will be more P extracted from PR with organic acids of low pH (Ivanova et al., 2006). According to International Institute of Tropical Agriculture (2010), a study from three different types of manure provided an indication that there was a positive relationship between the releases of P by low pH conditions. The study was conducted with manure obtained from pig dung, cattle and poultry. The study found that increase in organic acid lowered pH of the manure. The hydrogen and carboxyl (COOH) group in low pH organic acids enhances chelation of cations in phosphate rocks. This avails the P bounds in all the three cases determined (Adepetu, 2010). A comparison of two different types of acids (fulvic and humic) that have pH of 2.74 and 4.43 respectively showed that fluvic acid extracted more P from PR (9.08 µg mL^{-1}) compared to humic acid's extraction of 4.68 µg mL^{-1}. There is a different aspect of the PR that is also an important factor in ensuring P availability is optimum. Increase in volume or concentration of solubilizing agents increases amount of P extracted from PR and vice versa (Singh and Amberger, 1997; Agyarko et al, 2016). To this realization, it was determined that there were specific concentration ratios for different organic acids. For instance, fluvic acid would obtain maximum P extraction at a ratio of 6:1 whereas humic acid would obtain optimum extraction at a ratio of 4:1 of humic to PR (Singh and Amberger, 1997). Further studies were conducted and there was a realization that whenever there was an increase in the concentration of organic manure used to solubilize PR contributed to an increase in the amount of P available for plant yield and growth. This is scientifically explained by the fact that an increase in the organic P solubilizing materials results in higher microbial agents and -COOH groups increasing chelation of PR and P availability to plants (Singh and Amberger, 1997; Agyarko et al, 2016).

2.5.2 Use of compost and manure in managing phosphate rock

Efficiency of PR in crop production is also improved by composting with organic materials. Phosphorus is solubilized during composting by the humic substances which have chelating effects (Bangar et al., 1985). The total and available P content increases with decomposition improving P available for plant uptake. This results in improved crop growth and yields. Sharif et al. (2011) who composted PR with animal dung found that composting simple animal dung increased the extractable P by 105% compared to farm yard manure without PR. In addition, total nitrogen content of the final compost increased by 23% in simple animal dung composted with PR compared to simple farm yard manure. He attributed this to the microbial activity of the microbes in the animal manure in solubilizing PR. Ali et al. (2014) identified that composting, is a biological process that involves microorganisms such as bacteria and fungi that convert organic materials into humus. The microbes act on the organic materials by utilizing the carbon as the energy source to generate new microbial cells and in the process releases organic acids as one of the excretes which in turn solubilizes PR added in the compost. Bangar et al. (1985) attributes this increase in PR dissolution during composting to increase in the amount of acidic functional groups that have chelating effects. Incorporation of PR with manure and compost during planting is another way that has been identified for improving solubilization and efficiency of PR fertilizer (Agyarko et al., 2016). The rate of PR dissolution is significantly increased by mixing PR with manure and compost compared to direct application hence more P released resulting to improved crop growth and yield. In his study, Agyarko et al. (2016) found that application of 2.5g manure and 2.5g PR into a kilo of soil increased the available P by 4-7 times over direct application of PR at 2.5g

PR per kilo of soil. By doubling the amount of poultry and cattle manure to 5g and 2.5g PR into a kilo of soil, the amount of P released increased by over 50%. This increase in P released was attributed to increase in microbial activities and acidic condition created in the soil by the microbes during organic material decay. Vine (2012) stated that composted manure results in the improvement of soil acidity reduction and soil structure development which enhances root proliferation. The study observed that composting PR improved crop production through the control of variation in the availability of P and N in the PR environment. Even though it is determined that compost manure enables plant yield growth, Shukla (2013) observed that it is important to note that it is all about the ratios. Therefore, if P and N are produced in excess through the compost, there would be devastating results. Instead of improved yield, plants may wither. Hence, it is important that the compost manure on PR is managed properly. In his study in Southern Nigeria, Adepetu (2013) noted that the best soil structure for the crops planted should be understood so that it would not be an issue when the compost is piled up. The author added that the particular soil depth for different plants has to be determined for a particular optimum yield to be obtained. The Ibadan study conducted by Vine (2010) indicated that it is important to consider the cost for the maintenance of good and productive compost manure. Vine added in his findings that it is the expenses incurred that will determine whether the yield obtained is profitable or not.

2.5.3 Management of phosphate rock with microbial organisms

According to Adepetu (2010), phosphorus is an important macronutrient for plant growth; the phosphate in phosphorus is among the least soluble mineral nutrients in the soil. Besides, it is where microbial organisms play an important role. The International Institute of Tropical Agriculture (2010) conducted a study that concluded that micro-organisms aid in the solubilization of the insoluble organic minerals such as Phosphorus. Therefore, microbial organisms play an important part in plant growth and development as it enables the solubility of phosphorus for plant uptake. Adepetu (2010) reported that such microbial organisms include cyanobacteria, bacteria, fungi, and actinomycetes. He added that in this determination, there are other factors that were found to influence microbial solubilization. They include the soil moisture, pH, NPK and organic matter. The solubilization of phosphates varies in deficiency. Phosphate solubilizing micro-organism plays an important role in availing Phosphorus for plants; by dissolving the insoluble Phosphorus. To be able to maintain Phosphorus contents available in deficient areas for crop production, restoring soil phosphorus content is a priority. It is important that the local phosphate rock sources are used in the restoration process to reduce the cost incurred and improve soil fertility in the process. According to Shukla (2013), to maintain a fertile soil for crops to be able to absorb P, it is important that the P is kept in its soluble state even though in most cases only about 5% of P is usually soluble. In such cases, farmers are advised to use solubilizing microbial organisms to ensure that P is soluble and available for uptake during plants growth. This improves plant growth and yield. Shukla (2013) advised that in the event that phosphate solubility is becoming an issue, it is important that phosphate solubilizing test is conducted to enable necessary actions to be taken. The determination of this kind will require farmers to know their soil pH. Soil pH will determine the kind of phosphate solubilizer ratio that is required for optimum production.

2.6 Standard phosphorus requirement of crops

Standard phosphorus requirement (SPR) can be described as the concentration of PO_4^{2-} in the root medium or soil solution that is non-limiting to plant growth but provides for the optimum yield (Fox, 1981; Hue and Fox., 2010). The SPR of the soil is influenced by the soil and management factors. Soils factors that influence SPR include the buffering capacity of the soil for P; cross sectional area for diffusion of P to roots and toxicity of the diffusion path; and mineralization of organic P. Besides soil factors associated with root development especially root hair proliferation and mycorrhizal associations; species and concentration of salts in the soil; and temperature and nature of solid phase as it influences the rate of P dissolution determine the SPR of the soil. Management factors that influence standard P requirement include the volume of soil fertilized and placement of fertilizer with respect to the roots; and fertilization time in relation to expected utilization (Hue and Fox, 2010). Efficient management of soil and P fertilizer requirement requires knowledge of the quantity of P required in the soil to maintain the standard P concentration required by the crop being grown; and the standard P requirement of the plants being grown (Hue and Fox, 2010). According to Fox (1981), different SPR have been recommended for growth of crops regardless of soil characteristics. A soil solution of 0.05 mg L^{-1} is the recommended SPR for maize, yam and banana, 0.10 mg L^{-1} recommended for cowpea and sweet potatoes, 0.18 mg L^{-1} recommended for Irish potato and 0.20 mg L^{-1} recommended for chives, cabbages, tomatoes, soybeans, millet and eggplants. Standard P requirement of P fertilizer applied is determined from the phosphorus sorption curve and chemical extraction methods (soil test method) (Hue and Fox, 2010).

2.7 Availability of phosphorus in acidic soils

Acid soils are distributed all over the world covering about 11% of the total land and 40-70% of the arable and potentially agricultural arable land mostly in humid regions (Hede et al., 2001). In Kenya, acid soils cover about 13% of the agricultural land (Kanyanjua et al., 2002) most of which is the tea, coffee-tea and main coffee agro-ecological zones. Acid soils are characterized by low pH of below 6.5 as well as high levels of exchangeable acidity (Kanyanjua et al., 2002). The soils have relatively high content of aluminum (Al) ions that bind P from applied P fertilizer resulting to low availability of extractable P for plants uptake. Due to high levels of leaching in the regions as a result of high rainfall, the soils contain relatively low amounts of exchangeable cations such as calcium and magnesium ions. The organic matter in most of these soils is presumed to be high especially in soils near the forests or in highlands. The presence of organic matter is presumed to be the resulting aspect of relatively high concentrations of iron (Fe), copper (Cu), zinc (Zn) and manganese (Mn) ions in most of these soils.

High soil acidity has adverse effects on growth and development of most crops reducing their potential production and yields (Gweyi-Onyango et al. 2010). High soil acidity leads to toxicity of the plant roots due to increased Al and Mn accumulation in the soils. Fertility of the soil is as well reduced leading to: decreased productivity of plants; increased health risk of fodder crops to animals through hypomagnesaemia and hypocalcaemia; deficiency of molybdenum (Mo) and P to crops; as well as reducing the nitrifying and organic matter converting microbes. High acidification also results in reduced plant water use efficiency especially in the lowlands hence requiring constant recharge. Due to loss of soil cover, the soils are prone to increased erosion and water pollution as nitrates and other cations leach into them (Zheng, 2010).

Crops exhibit varying abilities to tolerate high Al concentration and increased soil acidity. Plants can therefore be categorized into very tolerant, medium tolerant, sensitive or very sensitive. According to Kanyanjua et al. (2002), tea, sweet potatoes, Irish potatoes and chillies are some of the plants that are able to tolerate and do well in very acidic soils. Most maize varieties are categorized under medium tolerance to sensitive range together with wheat and peas. However, most horticultural crops such as onions, carrots, spinach, cauliflower and cabbages are highly sensitive to soil acidity. Phosphate rock used as a liming material is effective in supplying Ca ions to plants growing in highly acidic soils. Studies have shown that application of PR raises soil pH improving plant growth (Zapata and Roy, 2004). Phosphate rock application in acidic soils increases the concentration of Ca ions that binds with Al ions in the soil decreasing the amount of extractable Al ions in the soil. Works done by Pearson in Zapata and Roy (2004), showed that application of PR in Puerto Rico's Ultisols and Oxisols soils lead to reduction of extractable Al from 60% to 20% and increase in the soil pH from 4.2 to 4.8. This shows the effectiveness of PR use in tropical soils that are highly weathered.

2.8 Determination of phosphorus sorption in soils

Phosphorus sorption in soil is determined using the phosphorus sorption isotherm models (Zhang et al., 2009). The amount of P sorbed by the soil colloids is determined by getting the difference between initial P concentration in a solution of known P concentration and the final P concentration after sorption by the soil samples (Samadi, 2006). Information on P sorption characteristics of the soil is important in: designing the appropriate management strategies of P especially for the high P fixing soils, making recommendations for the most profitable fertilizer use and determining the standard P requirements (SPR) which is the amount of P that must be sorbed and maintain enough P concentration for maximum yields of crops in soil (Zhang et al., 2009).

Langmuir model is the most commonly used method of P sorption determination. The model is used in soils that have homogenous sites of sorption. In addition, the model is used in soils where the adsorbed molecules do not interact; all adsorption occurs in a similar mechanism and at maximum adsorption, only a monolayer of the adsorbate molecules is formed (Moazed et al., 2010). Use of the Langmuir model is considered advantageous over the others since the maximum capacity of the P sorption in soil is determined and it can be used to determine the P binding energy which is energy that holds phosphorus to soil colloids. The two parameters are crucial in establishing the P loss potential of a soil (Zhang et al., 2009). Wolde, et al. (2015), employed this model in their work to determine the standard P requirement through determination of the maximum adsorption capacity which is the maximum amount of P that can be held per unit of soil. They indicated that soils with high maxima adsorption capacity have relatively large sorption site surfaces hence high sorption capacity. In addition, they used this method in defining the binding energy associated with each individual soil and related this to the other parameters such as the maxima sorption capacities, iron and aluminum content and the soil pH. Similarly, Gichangi et al. (2008) were able to employ the same model in determining the external P requirements and the maximum P adsorption capacity for soil samples in South Africa. By running a regression analysis of this data, the relationship between the sorption capacity and the soil property data on pH, Al and Fe content was clearly identified. However, the model alone falls short in including the sorbed legacy P which may result in erroneous estimates of sorption parameters. According to Amjad et al., 2003, a single surface Langmuir equation, which develops a linear line graph for a soil with homogeneous sorption site is as follows.

$$C/(x/m) = 1/Kb + C/b \qquad \text{Eq. 1}$$

Where: C represents the concentration of P in soil solution at equilibrium (µg g-1); x m^{-1} is the amount of P adsorbed per gram of soil (µg g^{-1}); Smax is the adsorption maximum, equal to the slope of the line; 1 $kSmax^{-1}$ is equal to the y-intercept and k is the sorption affinity constant.

On the other hand, Fredlich model of P sorption determination is applied where the soils have heterogeneous sites of sorption (Wolde et al., 2015). The model's equation fits suitably where the statistical analysis of the b (adsorption maximum) and k (adsorption affinity) constants differ (Amjad et al., 2003). This difference is attributed to adsorption taking place in different sites on the soil surface or occurring in layers, adsorption layers being nucleated in the sorption surfaces and variation in heat of adsorption due to surface heterogeneity. In their analysis, Kenyanya et al. (2014) found that the potassium adsorption data was well fitted with this kind of model due to heterogeneity of the soil sorption site. Due to its suitability they further used the same method in determining the optimal potassium requirements in the fertilizer for maximum maize yields. Similar findings were observed by Ahmed et al. (2015), who used two different soils from five different sites and noted positive correlation between the Freundlich constant and sorption capacities of P in the soils at 5% significant level. Mohammad et al. (2012), also found that the model gave a high correlation value of 0.88-0.99 on both calcareous and non-calcareous soils from eight different sites on their ability to retain high amounts of P in them. Idris and Ahmed (2012), used this method in determining the sorption capacity and the adsorption energy in six soils from Sudan. They noted that soils with high capacity factor are considered to have high adsorption factor compared to those that have low or smaller capacity factor. The Fredlich model equation is as in Eq. 2 where the graph of log C against log X is plotted.

$$\log \mathrm{X} = \log \mathrm{Kf} + 1/\mathrm{n}\log\mathrm{C} \qquad \text{Eq. 2}$$

Where: X is the amount of P adsorbed per unit mass of the soil (mg kg^{-1}); C is the equilibrium concentration (mg L^{-1}); Kf represent the capacity factor/ measure of sorption surface coverage (mg kg^{-1}); n is the constant related to bonding energy; 1 n^{-1} = slope of the curve; and Log Kf = y-intercept (Amjad et al., 2003).

Temkin is another model that has been used in different studies for P sorption analysis (Ozacar, 2003, Mohammad et al., 2012, Kenyanya et al., 2014 and Ahmed et al., 2015). The model contains a factor that considers the adsorbent and adsorbate interactions of the media. Temkin models fits in determining the zero solution sorption point as well as intensity of P in the soils of interest (Ahmed, et al., 2015). They used the model's equation to estimate the equilibrium points (EPC_0) of five soil samples which ranged between 0.05 and 0.45 mg dm^{-3}. The derivation of its equation is characterized by uniform distribution of sorption energy to a maximum binding level. The Temkin equation is as follows:

$$qe = RT/b \ln A + RT/b \ln Ce \qquad \text{Eq. 3}$$

Where a graph of amount of P adsorbed at equilibrium (mmol g^{-1}) (qe) versus natural logarithm of the residual P concentration (lnCe) is plotted and used to determine the values of A and b (Ozacar, 2003).

2.9 Management of phosphate rock for plant utilization

2.9.1 Effect of compost and phosphate rock on nutrient uptake and use efficiency

Phosphorus is an essential plant nutrient though due to its limited mobility in soil, deficiency of P is more frequent with low recovery efficiency of less than 20% (Zafar et al., 2017) and more than 80% of added P making it unavailable to plants. Phosphorus use efficiency (PUE) can be termed as a measure of how well plants use the available phosphorus nutrient in the planting media or soil (Roberts and Johnston, 2015). PUE can be described as the yield of plants in terms of biomass per unit of phosphate fertilizer applied to the plants (Eq. 6). The concept of PUE depends on the ability of plants to uptake the phosphorus supplied and available in the soil, transport it, store, mobilize and use the phosphorus within the plant. Determination of PUE is of importance for improvements of crops, maximize production in P deficient areas and minimize over use of phosphate fertilizers for environmental protection (Fageria et al., 2013). According to Johnston and

Syers (2009), PUE is composed of phosphorus recovery efficiency (PRE), which is normally assessed using the balance method that expresses the P removal from soil to input ratio as a percentage as:

$$\text{PRE (\%)} = \frac{\text{P uptake fertilized plot}\left(\frac{\text{kg}}{\text{ha}}\right) - \text{P uptake unfertilized plot}\left(\frac{\text{kg}}{\text{ha}}\right)}{\text{Amount of P applied}\left(\frac{\text{kg}}{\text{ha}}\right)} * 100 \qquad \text{Eq. 4}$$

Neto et al., (2016), further indicates that the PUE can be separated into nitrogen, phosphorus and potassium uptake which is the concentration of nutrient in plants multiplied with the dry matter 100^{-1} calculated as Eq. 5:

$$\text{NPK uptake}\left(\frac{\text{kg}}{\text{ha}}\right) = \frac{\text{NPK in plants}\left(\frac{\text{kg}}{\text{ha}}\right) * \text{dry weight of plants}\left(\frac{\text{kg}}{\text{ha}}\right)}{100} \qquad \text{Eq. 5}$$

$$\text{PUE}\left(\frac{\text{kg}}{\text{ha}}\right) = \frac{\text{Root yield from fertilized plot}\left(\frac{\text{kg}}{\text{ha}}\right) - \text{Root yield from unfertilized plot}\left(\frac{\text{kg}}{\text{ha}}\right)}{\text{Amount of P applied}\left(\frac{\text{kg}}{\text{ha}}\right)} \qquad \text{Eq. 6}$$

Strategies to increase P uptake and use efficiency has been assessed which include use of animal manure and organic fertilizers such as PR to increase crop production and improve soil fertility. Combining of organic manures and PR has increased the synergy and synchronization of nutrients increasing their uptake and use efficiency in crops. A study by Zafar et al. (2017) on effect of poultry manure and PR on wheat P uptake and PUE showed that combination of poultry manure and PR at ration of 1:1 resulted to the 167% increase in uptake of P over unfertilized soil with a PUE of 18%. By combining PR with poultry manure, the PUE increased to 86% over use of single superphosphate fertilizer. The authors attributed this increased uptake and PUE to increased solubilization of PR and complexation of P binding sites in the rhizosphere by manure making P available to plants. Similar results were reported by Jalil et al. (2017) in a study to assess the residual effect of PR, farmyard manure and effective microorganisms that high uptake of nitrogen, phosphorus and potassium in wheat grain was achieved by combining PR with farmyard manure. In their study Arif et al. (2018) reported a 27.5% increase in P recovery efficiency when compost was enriched with PR, phosphorus solubilizing bacteria PSB and single superphosphate. A 38.6 and 103.4% increase in N and P recovery efficiency respectively in compost enriched with PR and (PSB) over the unfertilized soils. Phosphorus recovery efficiency was highly increased (27.5%) by combining compost enriched with PR, PSB and single superphosphate. This is an indication that use of combination of PR with locally available organic materials/manures can be an effective affordable way of improving nutrients uptake and use efficiency of the crops in the farms.

2.9.2 Effect of compost and phosphate rock on crop yields

Crop yields are highly dependent on effective supply of the essential nutrients and ability of the plants to take up the nutrients. Adequate application of P fertilizer increases the growth and production of crops. Studies have shown that use of PR significantly increases the yield of crops (Sabrina et al., 2013; Jalil et al., 2017; Zafar et al., 2017). Studies by Gweyi-Onyango et al. (2010) on differential benefits of PR in tomato plants showed that application of PR increased the shoot dry weight by over 40% compared to treatments without P fertilization regardless of the N source. Addition of compost further increases the availability of P to plants increasing the yields of crops (Zafar et al., 2017). A study by Sabrina et al. (2013) assessing the effect of mixed organic-inorganic fertilizer on growth of Setaria grass (*Setaria splendila*) showed that vermicomposting PR for 90 days increased nutrient uptake and dry matter yield of the grass by increasing P availability from PR. A similar study by Jalil et al. (2017) application of PR and farmyard manure showed more wheat grain per spikes (48.5) and grain yield (4.98 tonnes/ha) compared to non-fertilized plants with wheat grain per spikes and grain yield of 41.26 and 2.72 tonnes ha^{-1} respectively.

2.9.3 Effect of compost and phosphate rock on soil characteristics

Compost manures have been used extensively to increase the fertility of soils in agricultural intensified soils. Irrespective of fortification with PR, compost manures raise the soil pH, cation exchange capacity (CEC), organic carbon, available nitrogen, phosphorus and potassium and cumulative respiration (Verma, 2013; Nagar, 2016). This is attributed to high pH, CEC and organic matter in the composts. Compost manure increases the water soluble P, microbial P, NaOH P, $NaHCO_3$ P and residual P. Verma (2013) investigating the effect of compost and PR on soil characteristics found that compost amended or un-amended with PR increased most of the soil P pools compared to soil without compost and PR amendment. Increase in labile and non-labile P in the soil is due to mineralization of compost and solubilization of P overtime. Compost increases soil particles aggregation aerating the soils (Verma, 2013). Composted materials improve the soil physical characteristics such as increasing soil porosity and infiltration, and water holding capacity (Nagar et al., 2016). In their study on the effect of organic manure and crop residue management on physical, chemical and biological properties of soil Nagar et al. (2016), found that addition of compost manure reduced the soil bulk density increasing the porosity and particle aggregation. Composts increase mobilization of P from the PR (Verma, 2013). This is evident by increase in labile and non-labile P pools with incorporation of compost and PR in soils during planting. The increase in available P pool is due to microbial decomposition of organic matter in the organic manure. Availability of P is further increased by decreasing the power of the phosphate precipitating cations such as Al, Fe and Ca ions through completion of the P binding sites in the soil particles. On the other hand, application of phosphate rock raises the soil pH (Gweyi-Onyango et al., 2010). A study by Jadin and Truong (1987) in Gabon with Oxisol showed that application of PR had a liming effect increasing pH by 0.5. High calcium carbonate content in PR lowers the soil acidity by reacting with hydrogen and the aluminium ions (Zapata and Roy, 2004). Reduction of the P binding effect of the Al^{3+} ions by Ca^{2+} ions increases the release of P in the soil. This is exhibited by build-up of the labile and non-labile P pools (Verma, 2013). According to Gweyi-Onyango et al. (2010), addition of PR led to Al complexation enhancing uptake of P which increased the P content of the tomato plant tissues. However, PR application is associated with Zn deficiency in calcareous soils. In their study, Gweyi-Onyango et al. (2010), a strong Zn deficiency was observed in Kibwezi site in treatments where PR was added which is attributed to complexation of the Zn ions with increase in soil pH.

CHAPTER THREE

GENERAL METHODOLOGY

3.1 Description of the study site

3.1.1 Geographical location of the study site

The phosphorus management study was conducted in already existing Long Term System Comparison (LTE) and Participatory Onfarm Research trial sites at Chuka and Thika; and Kangari and Kianjugu respectively. The sites are located in the sub-humid zones of central highlands of Kenya. Kangari, Kianjugu and Thika sites are located in Murang’a county and Chuka site at Tharaka Nithi county. Chuka site is situated at 1478 m above sea level (0^o20.864' S, 37^o38.792' S) in the premises of Kiereni primary school, 225 km from Nairobi (Figure 3.1). Kangari site lies at 2134 m above sea level (0^o46.500' S, 36^o51.150' S) at a farmer’s homestead behind Mwarano primary school, 85 km from Nairobi (Figure 3.1). Kianjugu site is located at 1328 m above sea level (0^o53.460' S, 37^o15.450' S), 74 km from Nairobi (Figure 3.1). Thika site is situated at 1500 m above sea level (1^o0.231' S, 37^o04.747' S) in the premises of Kenya Agricultural and Livestock Research Organization (KALRO), Horticulture Research Institute, Kandara, 45 km from Nairobi (Figure 3.1)

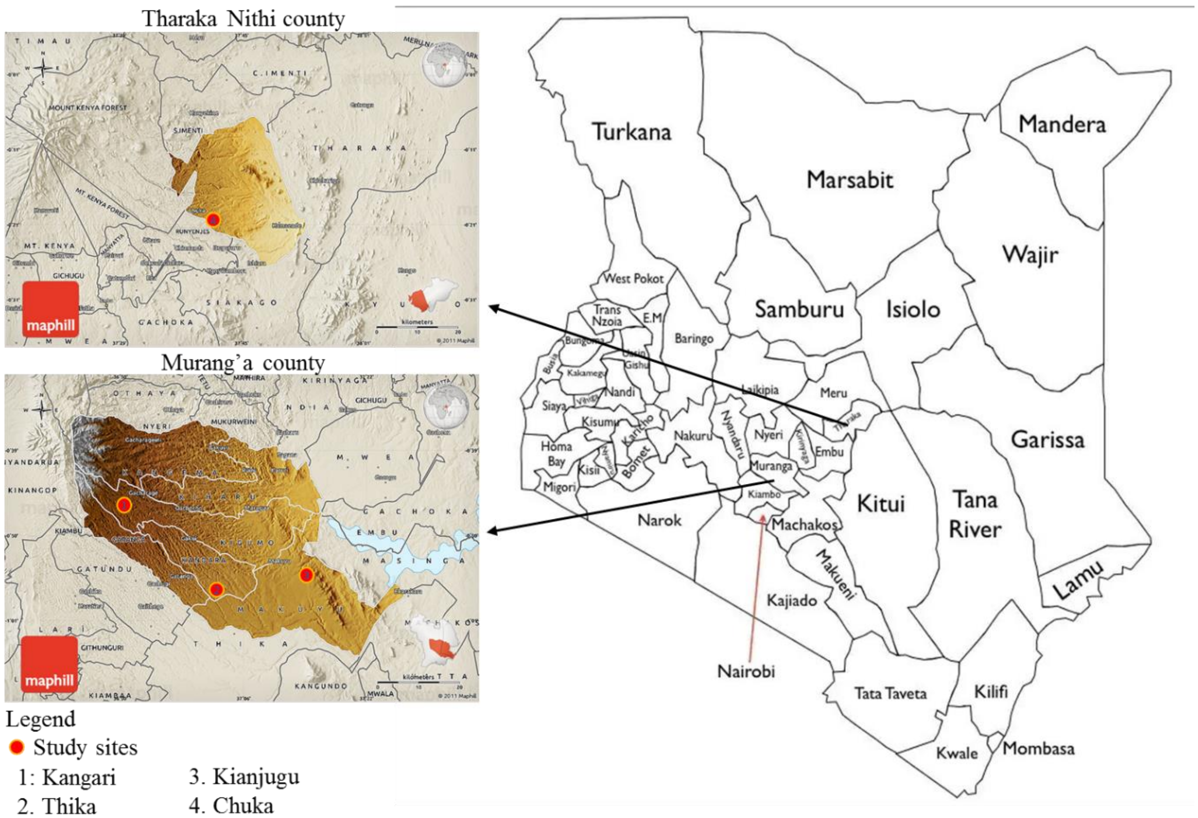

Figure 3.1: Geographical locations of Chuka, Kangari, Kianjugu and Thika sites in Tharaka Nithi and Murang'a counties (maphill.com, 2011)

3.1.2 Relief and drainage

Due to closeness to the Aberdare ranges which lie on the western side, Kangari site has a rugged topography with steep "V" shaped slopes and deep soils with good drainage. Chuka site is gently steep slopes with deep well drained soils. Thika site is relatively sloppy with well drained soils. Kianjugu site has gently steep slopes with inadequate soil and water conservation and low soil fertility (Jaetzold et al., 1983, Strobel et al., 1987).

3.1.3 Ecology and soil

Kangari site is located in the tea and dairy agro-ecological zone with humic Andosols with partly lithic phase (Jaetzold et al., 1983, Strobel et al., 1987). The soils here are characterized by good drainage, very deep profiles, and dark reddish brown to dark brown color, very friable and smeary texture, and clay loam to clay types with thick acid humic top soil and low pH levels (pH < 5.0). In addition, the soils are easy to till, have good water storage capacity and allow good rooting of plants. Chuka site is located on the main coffee agro-ecological zone which has humic Nitisols (Jaetzold et al., 1983, Strobel et al., 1987). These soils are extremely deep with a good drainage and dusky red to dark reddish brown color, has friable clay with acid humic topsoil. Thika site is located on the upper sunflower maize agro-ecological zone which has rhodic nitisols (Jaetzold et al., 1983, Strobel et al., 1987). The soils are characterized by a moderately deep to deep well drained dark red to yellowish red in color, friable, sandy clay loam to clay texture. Kianjugu site is located on the lower sunflower maize agro-ecological zone, which has orthic Acrisols characterized by excessively drained to well drained soils with deep to very deep profile and dark to dark yellowish brown color with varying texture with some places being gravelly (Jaetzold et al., 1983, Strobel et al., 1987). The soils are associated with acidic bedrock and low nutrient content.

3.1.4 Climatic conditions

The sites experience varying climatic conditions. Kangari experiences an equatorial type of climate, while Chuka and Thika experience a sub-tropical type of climate and Kianjugu experiencing semi-arid conditions. Kangari receives an annual rainfall of between 1400 - 1600 mm and has mean minimum and maximum temperatures of 15 and 22°C, respectively. Chuka receives a mean annual rainfall of 1323 mm with mean annual temperatures ranging from 19.2 - 20.6°C. On the other hand, Thika receives a mean annual rainfall of 840 mm and annual mean temperatures of between 19.5 - 20.7°C. Kianjugu site receives annual rainfall of below 900 mm and mean annual temperatures of between 26 – 30°C. All the sites have a bimodal rainfall pattern with long rains occurring from April to June and short rains from October to December.

Details of the soil properties of Kangari and Kianjugu sites and annual cumulative rainfall amount and distribution over the two experimental cropping seasons (bimodal) are shown in Table 4.1 and Figure 3.2. The Kangari site received a cumulative rainfall amount of 961.50 mm (confidence interval = 359.49 mm) in the long rain (LR) season and 696.00 mm in the short rain (SR) season (confidence interval = 273.92 mm). The Kianjugu site received a cumulative rainfall amount of 321.00 mm (confidence interval = 145.01) in the long rain season and 454.00 mm (confidence interval = 212. 82 mm) in the short rain season.

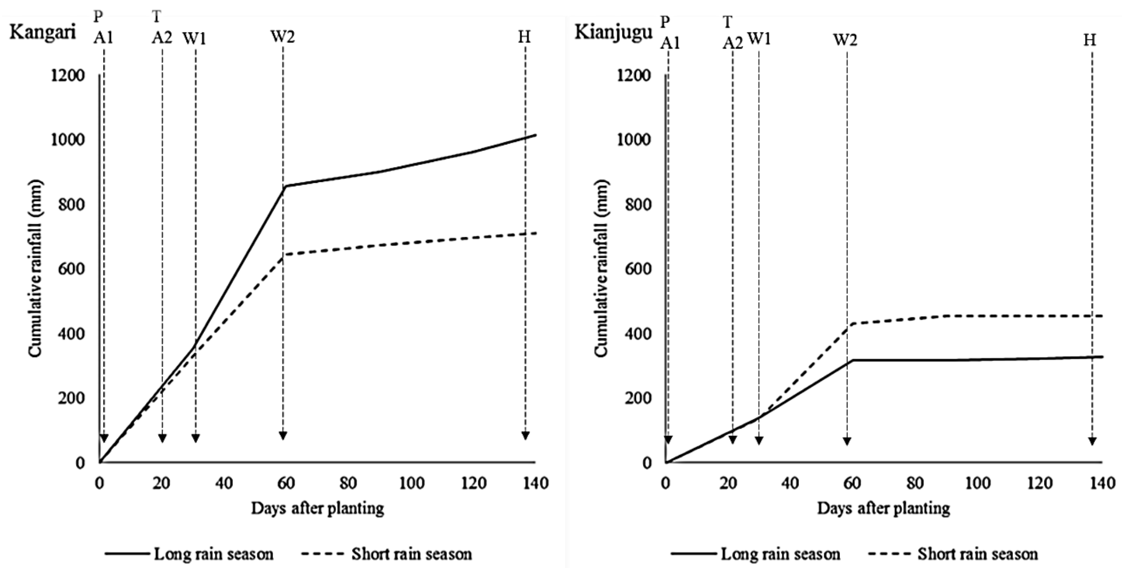

Figure 3.2: Cumulative rainfall distribution at Kangari and Kianjugu during the experimental trial period in the long rain season (April to August 2017) and short rain season (October 2017 to February 2018)

Confidence Interval 95%: Kangari = 117.37; Kianjugu = 65.38

P – Planting date for all the treatments

A1 – Input application (compost, phosphate rock (dissolved and powdered), triple superphosphate)

A2 – Input application of *Tithonia diversifolia*

T – Thinning

W1 – First weeding

W2 – Second weeding

H – Harvesting

3.1.5 Human and economic activity

As of 2009 Population and Housing Census, Murang'a and Tharaka Nithi counties had a population of 936,228 and 365,330 people respectively with a projection of 966,672 and 478,750 people respectively by 2017. Murang'a and Tharaka Nithi counties have an area of 2,326 km^2 and 2,610 km^2 respectively Farming is the main economic activity in most of these regions. Most of the farmers at Kangari concentrate on tea, dairy milk, maize and horticultural food crops production (Muindi et al., 2016). At Chuka, farmers focus on dairy and horticultural food production. Thika site is proximate to large pineapple, macadamia, mangoes and coffee plantations from Del Monte and Horticultural Research Institute. Real estate is another major economic activity in the area. Farmers at Kianjugu concentrate in production of maize, beans, mangoes, avocadoes and vegetable crops as the main economic activity.

3.2 Soil sampling, preparation and storage

Soils were sampled from both Kangari and Kianjugu sites. The land in each site was divided into 4 sub-plots where a composite sample was collected. Soils in each subplot were sampled using the zigzag pattern approach. The upper top layer of the soil was cleared (scooped off) using a shovel to a depth of 5 cm and soils collected at a depth of 5-20 cm. Soil samples per sub-plot was mixed thoroughly in a clean polythene paper or sack and 2 kg of soil per subplot taken and packed in sampling bags and labelled. The soils samples were carried in a cool box to ICIPE LTE lab for drying, sieving and storage. The soils were placed in clean paper sheets and air dried in a well-ventilated room until the soils were dusty. Soils were then homogenized by crushing the clods with a mortar and pestle followed by sieving through a 2 mm (35 Mesh) sieve to remove roots and gravel from the samples. The samples were then packed in sample bags, labelled and stored in a cool dry condition (Okalebo, et al., 2002).

CHAPTER FOUR

THE PHOSPHORUS SORPTION CHARACTERISTICS OF SOME SELECTED SOILS IN KENYA AND THEIR EFFECTS ON STANDARD P REQUIREMENTS AND P FERTILIZER APPLICATION

4.1 Introduction

Phosphorus (P) is one of the essential macro-elements required by plants for growth and development (Muindi et al., 2017). An adequate supply of P, through fertilizer application, is a key to increasing soil productivity and making agriculture profitable (Kanyanjua et al., 2002). When P is added to soils in the form of fertilizer, a series of reactions take place, ranging from the diffusion of P from the fertilizer granules into the soils solution, the sorption of P into the soil particles, and, with time, to P precipitation (Hedley and McLaughlin, 2005). Phosphorus is absorbed by plants in the form of orthophosphate, generally as H_2PO^{4-} or HPO_4^{2-}. The amounts of these ions in the soil solution depend on the sorption capacity of the soil which is determined by the type and content of layer silicate clay minerals, organic matter content, the amount of reactive aluminum (Al) or iron (Fe) compounds present and the soil pH (Borggaard, 2002; Samadi, 2006). Phosphorus adsorption increases with soil clay content (Idris and Ahmed 2012). Two layer (1:1) clay minerals have a greater anion exchange capacity (due to a positive surface charge e.g allophane clay minerals) and therefore a greater affinity for phosphate ions than smectite clay minerals with a negative surface charge (Juo and Fox, 1977). For example, 1:1 layers clay minerals have higher affinity and retention of phosphorus than 2:1 layers clay minerals (Idris and Ahmed, 2012). The surface charge of 1:1 clay minerals (and oxides) is partly pH dependent, so anion exchange capacity increases as pH decreases (Idris and Ahmed, 2012). Below pH 5.5, aluminum (Al^{3+}) and Al oxides become abundant and react more readily with phosphate to form aluminum phosphate, $AlPO_4$. At a pH of 3 and below, iron (Fe^{3+}) and Fe oxides reacts to form iron phosphate ($FePO_4$). At a pH above 5.5 phosphate increasingly reacts with calcium (Ca) to form calcium phosphate, $Ca_3 (PO_4)_2$. Calcium phosphates are relatively more water-soluble than $AlPO_4$ or $FePO_4$

and P availability is highest at a pH range of 5.5-7.0 (Pagliari et al., 2017). This means that $AlPO_4$ or $FePO_4$ are not readily available for plant use. In other words, in strongly acid soils, most of the P is bound or precipitated and cannot be released in the short or long term. Crops grown on such soils suffer from P deficiency (Kisinyo et al., 2013).

Agricultural land in Kenya covers about 48.55% of the total land area (Kassam et al., 1993; Trading Economics, 2020), out of which 13% is acidic (Kanyanjua et al., 2002) and is known to have a low availability of P, partly due to its sorption by Al^{3+}, Fe^{3+} and their oxides and this partly contributes to low crop productivity on these soils (Kanyanjua et al., 2002; Kisinyo et al., 2013). Such acidic soils include the acrisols, andosols and nitisols, which can also be found in the eight (8) counties of the Central Highland of Kenya (Jaetzold et al., 1983). In Kenya, fertilizer applications to such soils are largely based on blanket recommendation to farmers (Jaetzold et al., 1983; Kibunja et al., 2017). The recommendations of P fertilizers for vegetable production are also crop specific (Grubben and Denton, 2004). However, response to P fertilizers is expected to be both soil and crop specific (Juo and Fox, 1977; Hue and Fox, 2010). Elsewhere, it is known that soils vary in their P sorption capacities and standard P requirement (Gichangi et al., 2008; Idris and Ahmed, 2012; Kisinyo et al., 2013; Hadgu et al., 2014; Muindi et al., 2017). However, the above studies did not cover Humic andosols, Humic nitisols, Rhodic nitisols and Orthic acrisols. Beside, site-specific P fertilizer recommendations are required in order to optimize crop production and environmental management (Juo and Fox, 1977). Therefore, the study hypothesized that the different soil types (Humic andosols, Humic nitisols, Rhodic nitisols and Orthic acrisols) in the Central Highlands of Kenya will sorb P differently, influence standard P requirement of crops and will require different amount of P fertilizer to be applied. The objectives were to determine (i) the phosphorus sorption characteristics of the soils and their standard phosphorus requirements; and (ii) the factors responsible for phosphorus sorption, in order to recommend the P fertilizer required for different crops and soils, and the measures to improve P availability in the Central Highlands of Kenya. This is expected to contribute in preventing P deficiency and low crop yields (in high P binding soils), and P transportation from the site of intended use (especially in low P binding soils) to fresh water bodies via surface runoff and subsurface drainage.

4.2 Materials and Methods

4.2.1 Soil physical and chemical analysis

Soils were sampled from four sites: Kangari, Chuka, Thika and Kianjugu, all in the Central Highlands of Kenya. The soils are classified as Humic andosols, Humic nitisols, Rhodic nitisols and Orthic acrisols, respectively (Jaetzold et al., 1983). Prior to sampling, each site was divided into four quadrants and twelve soil samples were scooped from a depth of 5-20 cm and a composite homogenized sample was collected from each quarter and labelled. Thus four different soil samples were collected for each site for the soils (n=16). The soils were air dried, ground, sieved through a 2 mm size mesh and analyzed for their physical and chemical properties. The soil clay mineralogy was determined using the x-ray diffraction measurement procedures developed at World Agroforestry (ICRAF)'s Soil-Plant Spectral Diagnostics Laboratory (Shepherd 2010). The soils' physical and chemical characteristics were determined according to the procedures described by Okalebo et al. (2002). Soil particle size was determined using the Bouyoucos hydrometer method. Soil pH was determined by 1:2.5 soil: water suspension method. Soil organic carbon (SOC) was determined by the wet digestion method. Available phosphorous (Avail-P) was characterized with HCL and NH_4F in Bray 2 method and determined by the molybdenum blue method. Potential cation exchange capacity was determined using the summation method of exchangeable cations. Potassium (K), Sodium (Na), Calcium (Ca) and Magnesium (Mg) were determined by extraction with 1M of ammonium acetate adjusted to pH 7. Potassium (K) and Na were measured using flame photometry and Ca and Mg ions were measured using an atomic absorption spectrophotometer (AAS). Exchangeable micronutrients (Fe, Zn and Mn) were determined by extraction with 1% ethylenediaminetetraacetic acid (EDTA). Exchangeable aluminum content was determined by extracting with 1N potassium chloride and titration with 0.1M sodium hydroxide. Details of the physical and chemical soil characteristics of the soils are shown in Table 4.1.

Table 4.1: The physical and chemical characteristics of the soils from four sites (n=16) in the Murang'a and Tharaka Nithi counties of the Central Highlands of Kenya

Soil Property		Units	Chuka[a]	Kangari	Kianjugu	Thika[a]
Soil type			Humic nitisols	Humic andosols	Orthic acrisols	Rhodic nitisols
Sand		g kg^{-1}	162.5±4.8	500.0±21.2	522.5±14.9	185.0±9.6
Silt		g kg^{-1}	135.0±6.5	297.5±6.3	87.5±13.8	120.0±8.2
Clay		g kg^{-1}	702.5±8.5	202.5±21.0	390.0±13.5	695.0±15.0
Textural class			Clay	Loam	Sandy clay	Clay
pH (H_2O)			5.7±0.1	4.4±0.1	5.8±0.0	5.5±0.0
SOC		%	2.3±0.0	3.1±0.1	1.3±0.1	2.4±0.1
Avail-P		µg g^{-1}	28.8±1.9	19.4±0.2	6.4±0.9	12.3±0.5
Total Nitrogen		%	0.2±0.0	0.4±0.0	0.2±0.0	0.2±0.0
Exchangeable cations	K	µg g^{-1}	485.9±11.6	185.9±0.0	317.6±7.8	531.1±34.9
	Na	µg g^{-1}	45.6±2.9	545.6±44.6	545.6±33.1	34.9±1.8
	Mg	µg g^{-1}	271.1±9.9	83.4±6.8	216.1±5.4	244.9±17.2
	Ca	µg g^{-1}	1749.1±84.8	641.7±23.8	962.5±37.7	845.1±95.3
CEC		meq100g^{-1}	12.5±0.4	8.9±0.2	9.8±0.3	7.8±0.3
Al^{3+}		µg g^{-1}	1.1±0.2	70.8±3.3	0.0±0.0	6.4±1.6
Micronutrients	Fe	µg g^{-1}	81.3±2.3	140.9±2.6	127.3±13.4	54.6±0.9
	Zn	µg g^{-1}	11.9±0.4	2.3±0.2	5.9±0.8	7.1±1.3
	Mn	µg g^{-1}	951.6±12.2	17.4±1.7	773.1±88.3	528.7±11.6
Kaolinite		%	33.5±1.6	5.7±1.9	6.7±2.2	20.8±1.2
Gibbsite		%	1.1±0.7	25.1±1.3	1.1±0.4	0.9±0.5

[a] Data relating to the physical and chemical characteristics for Chuka (Humic nitisols) and Thika (Rhodic nitisols) was adapted from Adamtey et al. (2016) and selected clay mineralogy data (kaolinite and gibbsite) from Adamtey et al. (unpublished data).

Avail-P, available phosphorus; SOC , soil organic carbon; K, Potassium; Na, Sodium; Mg, Magnesium; Ca, Calcium; CEC, Cation Exchange Capacity; Al^{3+}, Exchange aluminum; Fe, Iron; Zn, Zinc; Mn, Manganese.

4.2.2 Phosphorus sorption and standard P requirement

Phosphorus sorption was determined using the batch method by equilibrating a known amount of soil with a solution of a known P concentration as reported by Okalebo et al. (2002). Six (6) equilibrating solutions of 0.01 M $CaCl_{2,}$ containing different levels of P concentrations (0, 20, 40, 60, 80 and 100 mg L^{-1}) were prepared from a stock solution of 1000 mg L^{-1} P. Samples of three (3) grams of soil were mixed with 30 mLs of equilibration solution in 50 mL plastic bottles. The mixture was (mechanically) shaken twice daily for 30 minutes at a temperature of 20 $^{\circ}$C and allowed to equilibrate overnight. This process was repeated over 6 days. Samples were then agitated at 3120 g in a Sanyo MSE Mistral 3000i centrifuge until the supernatant solution cleared and was then filtered using Whatmann's no. 542 filter paper. G-Force was used in place of revolution per minute (RPM) because the rotor size might differ and g-force may be different whilst the rpm stays the same (Blue et al. 2012).

$$\text{G Force (RCF)} = (\text{rpm})^2 \times 1.118 \times 10^{-5} \times r \qquad \text{Eq 7}$$

Where: g is reflective centrifuge force; and r is rotational radius in cm.

The P in the filtered aliquot was determined using molybdenum blue method and measured in a Bausch and Lomb Spectronic 20 Spectrophotometer at a wavelength of 882 nm. The amount of P sorbed was calculated as the difference between the initial P concentration in the equilibrating solution and the final P concentration in the filtered aliquot (Gichangi et al. 2008). P sorption data was fitted to the Langmuir equation (Eq. 1) to determine the sorption maxima and sorption affinity constant.

The amount of P sorbed was plotted against the concentration of P in the filtered equilibrating solution to show the pattern of P sorption isotherms of soils (Figure 4.1). The standard P requirement (SPR) for optimum plant growth was determined from the amount of P sorbed at standard supernatant concentration (Juo and Fox, 1977). This was achieved by substituting the x value from the regression equation (Eq. 8) from each of the P sorption isotherms (Figure 4.1) with concentrations of PO_4^{3-} solution shown in (Table 4.2).

$$y = mx + c \qquad \text{Eq. 8}$$

Where y is P sorbed at standard supernatant concentration which is the standard P requirement or the estimated P fertilizer requirement; m is the slope of the line; x is the standard supernatant or P solution concentration; and c is the y-intercept.

Table 4.2: Concentration of soil solution P (mg L^{-1} P) associated with optimum yield of selected crops in the study area

	Soil solution P (mg P L^{-1})	**Crop**
1	0.05	Banana (*Musa paradisiacal*)
		Maize (*Zea mays*)
		Taro (*Colocasia esculenta*)
2	0.1	Cowpea (*Vigna unguiculata*)
		Sweet potato (*Ipomea batatas*)
3	0.18	Irish potato (*Solanum tuberosum*)
4	0.2	Chinese cabbage (*Brassica oleracea*)
		Eggplant (*Solanum melongena*)
		Millet (*Pennisetum glaucum*)
		Soybean (*Glycine max*)
		Tomato (*Lycopersicon esculentum*)

Source: Hue and Fox, 2010

The standard supernatant or solution P concentrations are critical concentrations of P in soil solutions for the optimum growth of a specific crop. The values of solution P used in the study correspond to the major crops grown in the study area (Table 4.2). The amount of P required per hectare per season was calculated using (Eq. 9).

Amount of P required (kg ha^{-1} season^{-1}) =

$$\frac{\text{P required to meet SPR (mg kg}^{-1}\text{) x soil depth (0.20 m) x bulk density (kg m}^{-3}\text{) * area of a hectare (m}^{2}\text{) * 1000}}{1000000} \quad \text{Eq. 9}$$

The P_2O_5 content of triple super phosphate (TSP) is between 44-66%, so the number of TSP fertilizer bags to be applied to meet the SPR of the soils per hectare per season based on the P content of TSP which is 20% (on the average) was calculated using (Eq. 10).

$$\text{Number of 50 kg TSP fertilizer bags (bags ha}^{-1}\text{ season}^{-1}\text{) = (Amount of P required (kg ha}^{-1}\text{ season}^{-1}\text{)/ 20) * 2} \quad \text{Eq. 10}$$

Assumptions

Soil P can be replenished with either soluble P fertilizers, direct application of sufficiently reactive PR, or the combination of soluble P fertilizers and PR. Phosphorus can be replenished either immediately with a large, one time P application or gradually with moderate seasonal application at rates sufficient to increase availability of soil P (Buresh et al., 1997). A P solution concentration of 0.2 mg L^{-1} and above, is reported to support plant growth and development. Therefore the total fertilizer to be applied per hectare was based on the SPR.

4.2.3 Statistical analysis

The sorption isotherm data obtained was subjected to analysis of variance (ANOVA) using the *agricolae* function in R statistical software version 3.3.2 (R Core Team, 2018) with sites as fixed factors. The separation of the means for sorption isotherm parameters among the different sites was done by Tukey's honest significant difference method using the *emmeans* package at 5% level of significance with R statistical software (R Core Team, 2018). To determine soil properties responsible for P sorption in each soil type, a linear regression was conducted between the phosphorus sorption parameters and the soils' properties using *lm* function in *lme4* package, again at 5% level of significance (R Core Team, 2018).

4.3 Results

4.3.1 Phosphorus sorption

Between 76 and 81% of the P added during the equilibration of the soils from Kangari (Humic andosols), Chuka (Humic nitisols) and Thika (Rhodic nitisols) was sorbed, whilst less than 50% was sorbed in the soils from Kianjugu (Orthic acrisols) (Table 4.3). The sorption isotherm for the soils showed different capacities in adsorption of P (Figure 4.1), with the highest P adsorption in the Humic andosols and Humic nitisols, and a low P adsorption in the Orthic acrisols. The adsorption maxima (Smax) ranged from 392 to 1000 µg g^{-1} P with a mean value of 815 µg g^{-1} P (Table 4.3). The adsorption maxima for Humic andosols and Humic nitisols was significantly higher ($p < 0.001$) than in the Rhodic nitisols and Orthic acrisols. The sorption affinity constant (*k*) for the soils' P retention ranged from 0.02 L mg^{-1} in Orthic acrisols to 0.29 L mg^{-1} in Humic nitisols. The standard P requirement (SPR) was lowest (64 µg g^{-1} P) for Orthic acrisols and highest (249 µg g^{-1} P) for Humic nitisols (Table 4.3).

Table 4.3: The phosphorus sorption characteristics of soils from four sites in the Murang'a and Tharaka Nithi counties in the central highlands of Kenya

Site	Soil types	Percentage of added P sorbed	Adsorption maxima	Sorption affinity constant	Coefficient of Langmuir adsorption model
			(µg g^{-1})	(L mg^{-1})	R^2
Chuka	Humic nitisols	81.29^{a}	999.77^{a}	0.29^{a}	0.98
Kangari	Humic andosols	80.60^{a}	1000.00^{a}	0.12^{ab}	0.99
Kianjugu	Orthic acrisols	45.67^{b}	392.35^{c}	0.02^{b}	0.88
Thika	Rhodic nitisols	76.89^{a}	871.21^{b}	0.07^{b}	0.93

Means compared with Tukey's honest significance difference test ($p<0.01$).
Data on sorption affinity constant was presented in 3 decimal places to clearly show the precision
Values followed by the different letters shows a significant difference among treatment means at ($p < 0.05$).
The R^2 value shows that the equilibration data (P remaining in soil + solution, and P sorbed data) obtained during analysis fits the Langmuir adsorption model.

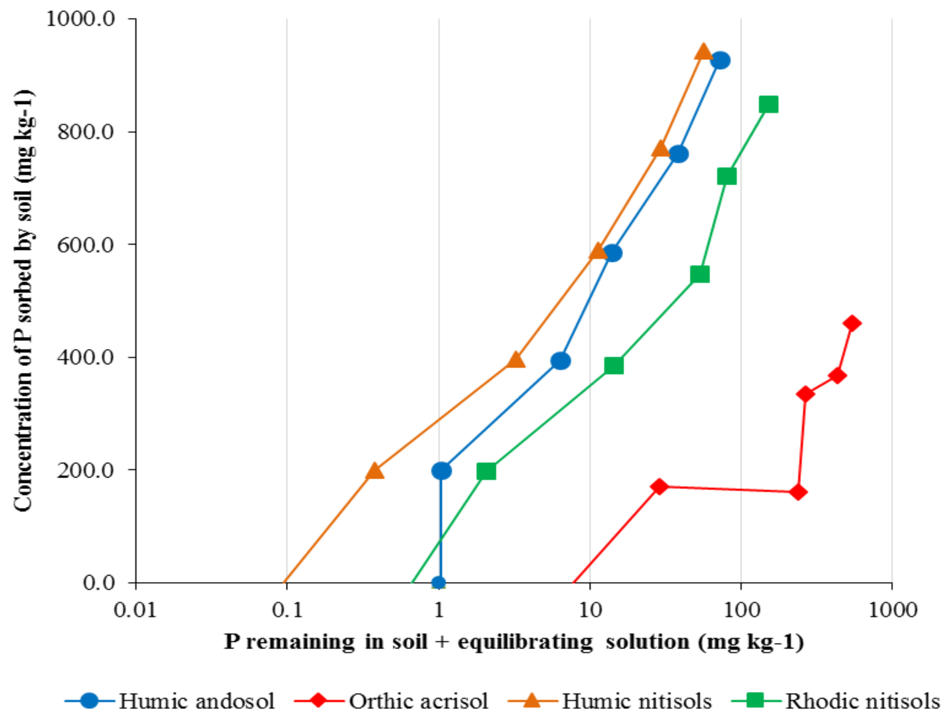

Figure 4.1: Trend of P sorption isotherms of four soils from Central highlands of Kenya

4.3.3 Relationship between sorption parameters and soil properties

Phosphorus adsorption maxima (Smax) showed a positive and significant ($p < 0.01$) relationship with organic carbon and a negative and significant ($p < 0.05$) relationship with pH (Table 4.4). In the Humic nitisols, a regression of Smax against soil properties (Table 4.4) showed a positive and significant ($p < 0.01$) relationship with kaolinite, Ca and CEC, and a significant ($p < 0.05$) negative relationship with Fe. In Humic andosols a positive and significant ($p < 0.01$) relationship between Smax and gibbsite, and Fe was observed. In Rhodic nitisols, Smax showed a positive and significant ($p < 0.05$) relationship with gibbsite, kaolinite, SOC and clay, but a negative and significant ($p < 0.01$) relationship with Al^{3+}. In Orthic acrisols the relationship between Smax and soil properties was positive and significant ($p < 0.05$) with gibbsite, but negative and significant ($p < 0.01$) with kaolinite.

Table 4.4: The relationship between adsorption maxima and selected soil characteristics of the four sites in the Murang’a and Tharaka Nithi counties in the Central Highlands of Kenya

		Humic nitisols			**Himic andosols**			**Orthic acrisols**			**Rhodic nitisols**			**All soils**		
Soil property	**Units**	Slope	Intercept	R^2	Slope	Intercept	R^2	Slope	Intercept	R^2	Slope	Intercept	R^2	Slope	Intercept	R^2
pH		-0.03 ^{ns}	31.76	0.24	-0.10 ^{ns}	106.37	0.74	0.00 ^{ns}	5.36	0.74	0.00 ^{ns}	5.50	1.00	-0.001 *	6.30	0.24
CEC	meq 100 g^{-1}	1.31 **	983.50	0.99	2.08 ^{ns}	981.38	0.85	21.20 ^{ns}	183.76	0.08	-3.14 ^{Ns}	895.67	0.00	0.001 ^{ns}	9.09	0.01
Ca	µg g^{-1}	0.01 **	984.95	0.99	0.28 ^{ns}	822.86	0.86	-0.01 ^{ns}	401.11	0.00	-0.04 ^{Ns}	904.90	0.01	0.312 ^{ns}	795.08	0.03
Fe	µg g^{-1}	-0.94 ^{ns}	1076.33	0.90	0.32 **	955.36	0.99	-0.42 ^{ns}	445.75	0.06	-15.00 ^{Ns}	1689.50	0.36	-0.040 ^{ns}	133.97	0.08
Kaolinite	%	0.39 **	986.69	0.99	1.08 ^{ns}	991.97	0.08	-199.30 **	2171.12	0.99	133.53 *	-347.24	0.98	0.017 ^{ns}	1.01	0.15
Gibbsite	%	3.63 ^{ns}	992.72	0.51	1.55 *	961.05	0.98	168.20 *	207.33	0.95	195.89 *	538.20	0.96	0.018 ^{ns}	0.07	0.20
SOC	%	1.32 ^{ns}	996.69	0.06	11.85 ^{ns}	963.82	0.62	203.95 ^{ns}	653.92	0.83	755.87 *	-2193.82	0.91	0.003 **	0.52	0.42
Al^{3+}	µg g^{-1}	-163.67 ^{ns}	1002.64	0.77	23.53 ^{ns}	981.53	0.85	na	na	na	14631.11 *	1087.02	0.95	0.001 ^{ns}	0.28	0.19
Clay	g kg^{-1}	0.00 ^{ns}	996.50	0.01	-0.04 ^{ns}	1007.29	0.68	0.29 ^{ns}	280.72	0.03	1.38 *	-88.20	0.92	0.162 ^{ns}	365.69	0.22

^{ns} not significant; * $p < 0.05$; ** $p < 0.01$;
na, not applicable because exchangeable is zero.
CEC - Cation exchange capacity’ Ca – calcium, Fe – iron; SOC – soil organic carbon; Al^{3+} - exchangeable aluminum.

4.3.4 SPR and the estimated amount of fertilizer applied

The standard P requirement (SPR) of the soils varied with Humic nitisols showing higher SPR followed by Humic andosols, Rhodic nitisols, and lastly by Orthic acrisols (Table 4.5). The amount of fertilizer P or TSP that would be required per hectare in a season to support crop growth and optimum yield in the Humic nitisols was (on average) 17 to 20% higher than that required in the Humic andosols and Rhodic nitisols, and 3 times higher than for Orthic acrisols. On every hectare of land cultivated, between 16 to 48 bags of TSP fertilizer would be required to meet the SPR of the different soil types in each season. In each soil type, variations in soil solution P had little effect on the SPR and the amount of P fertilizer or TSP that would be required.

Table 4.5: The estimated cost of TSP fertilizer use due to P sorption in conventional farming

	*Soil solution P (mg L^{-1})	Humic Nitisols	Humic andosols	Orthic acrisols	Rhodic Nitisols
Amount of P required to meet SPR** (µg g^{-1})	0.05	247.16	236.12	64.60	200.91
	0.10	247.86	236.67	64.64	201.16
	0.18	248.99	237.54	64.69	201.55
	0.20	249.27	237.76	64.71	201.65
Amount of P required in a hectare per season to meet SPR (kg ha^{-1} $season^{-1}$)	0.05	481.34	413.02	161.38	401.62
	0.10	482.71	413.98	161.48	402.12
	0.18	484.91	415.50	161.60	402.90
	0.20	485.45	415.89	161.65	403.10
Amount of 50 kg TSP fertilizer bag required to meet SPR (bags ha^{-1} $season^{-1}$)	0.05	47.96	41.15	16.08	40.01
	0.10	48.09	41.24	16.09	40.06
	0.18	48.31	41.40	16.10	40.14
	0.20	48.37	41.43	16.11	40.16

*Soil solution P corresponds to the different crop requirements for the major crops grown in the study area (see Table 4.2).

**SPR = Standard phosphorus requirement, i.e the concentration of PO_4^{3-} in the root medium (or soil solution) that is non-limiting to plant growth but provides for optimum yield

TSP = Triple superphosphate

4.4 Discussion

4.4.1 Soil properties influence on phosphorus sorption capacity

At Chuka, the adsorption maxima (Smax) in the Humic nitisols was higher than the adsorption maxima from Orthic acrisols and Rhodic nitisols at Kianjugu and Thika (Table 4.3). This can largely be attributed to the differences in their gibbsite, Ca, CEC, and to some extent kaolinite content (Table 4.4). Gibbsite has large surface area which influences P sorption reactions (Muindi et al., 2017), and P sorption increases with the clay content (1:1 clay type) (Idris and Ahmed, 2012). The moderately acidic medium of the Humic nitisols soil was expected to increase Ca's affinity to precipitate P to form calcium phosphate, $Ca_3(PO_4)_2$. According to Pagliari et al. (2017) at a pH of 5.5-7.0, the $Ca_3(PO_4)_2$ could become soluble in water with a possible increase in P availability in solution for uptake by plants. The positive and significant relationship between Ca and Smax supports previous reports that a high soil pH (above 5.5) can increase the affinity of Ca for P precipitate (Baker et al., 2013; Pagliari et al., 2017). High clay content and Ca in the soil increases the CEC, which increases the positively charged sites of the soil that reacts and binds the negatively charged phosphate ions from the soil solution (Hadgu et al., 2014). On the other hand, the negative relationship between Smax and SOC in the Rhodic nitisols (Table 4.4) implies that organic matter can play a role in inhibiting adsorption of P to surface clay minerals in such a soil (Hunt et al., 2007; Abolfazli et al., 2012). Due to time limitations, the study could not evaluate this assertion. It is therefore important to conduct further studies to evaluate the importance of organic matter in improving P availability on such soils. The negative relationship between Smax and exchangeable Al^{3+} or Fe is in line with earlier reports that these ions adsorb phosphate in soils with a pH of less than 5.5 (Kisinyo et al., 2013; Muindi et al., 2017).

The high adsorption maxima for Humic andosols can be attributed to its high gibbsite and iron content and that of Rhodic nitisols to high gibbsite and kaolinite content (Table 4.4). Gibbsite significantly influenced the adsorption maxima in the Orthic acrisols, although the adsorption maxima was comparatively low, which can be attributed to its low kaolinite content and the possible influence of soil organic carbon. Gichangi et al. (2008) similarly reported low adsorption maxima (192.3 µg g^{-1}) in acrisols at Qunu (in South Africa). Kisinyo et al. (2013) also reported that gibbsite clay minerals and Al^{3+} accounted for high adsorption maxima in Humic andosols in the Central Highlands of Kenya. The Humic nitisols and Rhodic nitisols had a higher kaolinite content than Humic andosols and Orthic acrisols and this could explain the positive and significant relationship with Smax in the first two sites. This suggests that the adsorption of P by kaolinite is dependent on its content in the soil through the precipitation of Al-P compounds and the slow dissolution and release of Si and Al and the ligand exchange of surface hydroxyl with phosphate ions (Samadi, 2006; Penn and Warren, 2008). Samadi (2006) and Muindi et al. (2017) have both reported that kaolinite causes high P sorption and retention in Inceptisols in Western Azarbijan (Iran) and in Humic nitisols in Meru (Central Highlands of Kenya). The low adsorption maxima and sorption affinity constant for the Orthic acrisols implies that more P would be available for plant uptake and use. Thus, care should be taken on such soils during P fertilizer application in order to avoid over-application, which can cause economic losses and adverse environment effects (Sharpley, 2000). The significant differences in the amount of added P adsorbed in the four soil types can be attributed to variations in the content of their gibbsite and kaolinite clay minerals and aluminum, as explained above. On the other hand, soil pH and organic carbon could explain the variations in the Smax when the soils were pulled together (Table 4.4). To enhance P availability in the above soils, application of organic matter such as compost and manure and lime (CaO) are recommended (Muindi et al., 2015; Mwangi et al., 2020). This is because organic matter contains functional groups (-OH and –COOH) that could compete with phosphate ions or form complexes with the mineral adsorption sites e.g Ca and Fe (Hunt et al., 2007; Abolfazli et al., 2012) which were observed in Humic andosols and Rhodic nitisols. The organic matter could also inhibit P sorption to gibbsite and kaolinite (Hunt et al., 2007) and thus can also be applied in soils such as Humic nitisols and Orthic acrisols. On the other hand, lime could reduce P adsorption in the above moderately to strongly acidic soils (Muindi et al., 2015).

4.4.2 Implications of P sorption on SPR and the amount of fertilizer applied

The SPR at soil solution of 0.2 mg L^{-1} P for Humic nitisols and Rhodic nitisols were in the ranges (208-435 µg g^{-1}) reported for nitisols in Kenya by Muindi et al. (2017). In contrast, the SPR for Orthic acrisols was higher than the 5 µg g^{-1} reported by Gichangi et al. (2008) on similar soil in South Africa. The differences in the results can be explained by difference in the clay content and mineralogy and other soil properties such as soil organic carbon (Kisinyo et al., 2013; Muindi et al., 2017). Soils with an SPR of between 50 to 100 µg g^{-1} are classified as low binding soils, those with an SPR between 100 to 500 µg g^{-1} classified as medium binding, and those with 500 to 1000 µg g^{-1} or over 1000 µg g^{-1} as high binding and very high binding respectively (Juo and Fox, 1977). Based on the above classification, the Humic andosols, Humic nitisols and Rhodic nitisols in the study area can be classified as medium P binding soils and Orthic acrisols as low P binding soils. Thus, the SPR for the Humic andosols, Humic nitisols and Rhodic nitisols indicates that the recommended P fertilizer rates for growing most crops in the region (e.g. 38 kg ha^{-1} P for maize) (Oseko and Dienya, 2015) may not be adequate for optimal crop production. This is because about 76 to 81% of these recommended P fertilizer rates would be adsorbed when applied, leaving around 7.22 - 9.12 kg ha^{-1} P, which is far below the soils SPR of 402 – 481 kg ha^{-1} P required for growing maize crop in the study area (Table 4.5). The consequences of this may include P deficiency in crops resulting in low crop yields (Kisinyo et al., 2013; Adamtey et al., 2016) and low financial returns (Adamtey et al., 2016) to the farmer. Similarly, the low SPR for Orthic acrisols in Kianjugu may suggest that over application of P fertilizer on such soils could lead to the washing away of residual P from farms into nearby water bodies during and after heavy precipitation (Sharpley, 2000). Further studies can investigate this assertion. The wide variation in the SPR for the soils suggest that a blanket application of P fertilizer is not appropriate across the different soils (Gichangi et al., 2008). First, for crops with soil solution phosphorus of 0.05 mg L^{-1} such as banana (*Musa paradisiacal*), maize (*Zea mays*) and taro (*Colocasia esculenta*), the phosphorus to be applied per season per hectare would be 413 kg on Humic andosols, 481 kg on Humic nitisols, 402 kg on Rhodic nitisols and 161 kg on Orthic acrisols. Second, for crops with soil solution phosphorus of 0.1 mg L^{-1} such as cowpea (*Vigna unguiculata*) and sweet potato (*Ipomea batatas*), the phosphorus to be applied per season per hectare would be 414 kg on Humic andosols, 487 kg on Humic nitisols, 402 kg on Rhodic nitisols and 162 kg on Orthic acrisols. Third, for crops with soil solution phosphorus of 0.18 mg L^{-1} such as Irish potato (*Solanum tuberosum*), the phosphorus to be applied per season per hectare would be 416 kg on Humic andosols, 485 kg on Humic nitisols, 403 kg on Rhodic nitisols and 162 kg on Orthic acrisols. Lastly, for crops with soil solution phosphorus of 0.2 mg L^{-1} such as Chinese cabbage (*Brassica oleracea*), eggplant (*Solanum melongena*), millet (*Pennisetum glaucum*), soybean (*Glycine max*) and tomato (*Lycopersicon esculentum*) the phosphorus to be applied per season per hectare would be 416 kg on Humic andosols, 485 kg on Humic nitisols, 403 on Rhodic nitisols and 162 kg on Orthic acrisols (Table 4.5). In the subsequent seasons, the amount of phosphorus fertilizer to be applied would be based on the specific crop requirements. The marginal variations in the SPR at soil P solution of 0.05 to 0.2 mg L^{-1} or in the phosphorus application rates within the same soils suggest that we can use 0.2 mg L^{-1} as an optimum P concentration to determine P fertilizer required to grow different crops such as maize, cowpea, Irish potato, cabbage (Juo and Fox, 1977) and carrots used in the subsequent study.

4.4.3 Limitations of the study

It is important to note that the amount of P to be sorbed to an equilibrium is dependent on temperature and specific surface area of the soil and adsorbent. In natural sense, soil is continuum and compact thus, the surface area of soils used in the isotherm study may not reflect the actual situation in the field. The soils used in the lab might have higher surface area thereby sorbing more P than may be happening under field conditions. Secondly, the soils in the lab do not take into account the complicated immobilization and remobilization relationship for P in the soil in the long-term response to P fertilizer application. Thirdly, due to the limited number of sample size (n=16), our findings on the relationship between soil sorption characteristics and soil properties cannot be generalized to cover the Central

Highland of Kenya. It is therefore important to increase the sample size to cover most of the counties in this region.

4.5 Conclusion

The four soils differed in their capacity to adsorb phosphorus. The Humic nitisols, Humic andosols and Rhodic nitisols can be classified as medium phosphorus fixing soils whilst the Orthic acrisols classified as low phosphorus fixing soils. Soil mineralogy (gibbsite, kaolinite, calcium, and iron) have been identified as the major factors that influence phosphorus sorption in the Humic andosols, Humic nitisols, Rhodic nitisols and Orthic acrisols. The soils showed a wide variation in their standard phosphorus requirements indicating that the blanket application of phosphorus fertilizer as being practiced in Kenya is not appropriate.

CHAPTER FIVE

MANAGING PHOSPHATE ROCK TO IMPROVE NUTRIENT UPTAKE, PHOSPHORUS USE EFFICIENCY AND CARROT YIELDS

5.1 Introduction

Phosphorus (P) is one of the macronutrients required for plant growth and development (Syers et al., 2008). In most tropical soils, the availability of phosphorus to plants is strongly influenced by the binding effects of aluminum (Al) and iron (Fe) ions in acidic soils with pH < 5.5, and calcium (Ca) and magnesium (Mg) in basic soils with pH > 8 (Costa et al., 2016; Yadav et al., 2017). Thus, only 10-25% of mineral P fertilizer applied to soils is recovered and utilized (Kisinyo et al., 2014), resulting in reduced maize grain yields by 16-28% in Kenya (Ligeyo, 2007). This implies that most soils in Sub-Saharan Africa (SSA) require substantial amounts of P inputs to meet the standard P requirement (SPR) of crops (Kisinyo et al., 2014). This raises problems for many small-scale farmers in SSA as mineral fertilizers are often either unavailable or prohibitively expensive (Verde et al., 2013). Phosphate rock (PR) provides a cheap source of P (Zapata and Roy, 2004) and an alternative, especially relevant for organic farming systems (Adamtey et al., 2016). Minjingu phosphate rock (MPR) from Tanzania occurs in both soft and hard form containing carbonate apatite and may differ in consistency, fabric, and other accessory minerals (Msolla et al., 2005). About 60% of MPR exists as hard PR that are hard to disaggregate with very low solubility in acidic soils (Chien et al., 2010), with a P recovery efficiency of less than 5% (Zapata and Zaharah, 2002).

There is a need to sustainably intensify agricultural production systems in SSA in order to enhance productivity, food security, and incomes. In this context, it is important to develop novel, soil-specific technologies, pilot tests, and transfer them to farmers (https://systems-comparison.fibl.org/about.html). This points to the need to find better ways to manage PR to enhance P availability to plants and increase agricultural productivity.

Several studies have identified different possible ways to increase P availability from PR: grinding it and combining with compost (Nishanth and Biswas, 2008) or manure (Zafar et al., 2017), solubilizing it in milk sludge also known as buttermilk (Cicek et al., 2020), or making use of phosphate solubilizing microorganisms (bacteria and fungi) (Abbasi et al., 2015; Panhwar et al., 2013). Low molecular weight organic acids (such as oxalic, malic, citric, lactic, malonic, tartaric, and succinic) have also been used to solubilize P from PR (Jamal et al., 2018; Klaic et al., 2017; Wahba et al., 2018). However, the P recovery efficiencies from the first two approaches are only between 18% and 29% (Zafar et al., 2017). Farmers in SSA lack the knowledge and skills to use P-solubilizing bacteria (PSB) and fungi and lack access to PSB inoculants (Mukhongo et al., 2016) and there is inadequate information on how to use milk sludge or organic acids to dissolve PR (Cicek et al., 2020; Zapata and Zaharah, 2002). Information on the use of natural acids from organic materials, suitable ratio of PR to organic material concentrations, and the optimum time for PR dissolution are limited (if available at all). Furthermore, studies on the solubilization of PR have not assessed the impact of dissolved PR on the efficiency of P recovery (Roy et al., 2018). In Kenya, organic materials such as lemon and pineapple fruits are easily available and accessible (especially in Murang'a County). The juices from these fruits contain large amounts of organic acids (Nour et al., 2010; Xin-Hua et al., 2014) that could dissolve PR (Chien et al., 2010; Osman, 2015). However, the efficiency of these juices has not been tested; hence this paper aims to fill this and the gaps mentioned above. The study which was conducted within the framework of the SysCom program (https://systems-comparison.fibl.org/about.html) and hypothesizes that: (i) juices from citrus and pineapple waste, the ratio of juice to PR powder and the length of time of dissolution will not influence PR dissolution, i.e., the release of available P into the solution; (ii) dissolved PR, applied directly together with compost, or composted with animal manure, crop and plant residues will not improve carrot P recovery efficiency, and yield less than powdered forms of PR or triple superphosphate (TSP) applied directly with and without compost. The objectives of this study were to assess; (a) the efficiency of lemon and pineapple juices and the concentration and time needed to release more than

50% of available P from PR, and; (b) the effect of different types of PR management on carrot yields, nutrient uptake and P-use efficiency.

5.2 Materials and Methods

5.2.1 The management of phosphate rock (PR)

5.2.1.1 An assessment of the efficiency of organic juices on PR dissolution

Lemon and pineapple fruits were collected from around Thika and the juices extracted. Samples of one hundred (100) gm of Minjingu phosphate rock (MPR) obtained from Tanzania, with a total P content of 14.58%, were weighed into 1000 mL plastic containers. Five different volumes of lemon and pineapple juices and distilled water (100, 200, 300, 400, and 500 mL) were added to the MPR, giving fifteen different treatments. Twenty (20) lemon fruits with an average weight of 50 g per fruit and two pineapple fruits with an average weight of 1000 g per fruit were used to extract a liter of each juice. The initial chemical characteristics of the lemon and pineapple juices and distilled water used in the dissolution experiment were as shown in Table 5.1. Each treatment was replicated three times. The solutions were stirred with a sterile glass rod for 30 minutes on each day of sampling to ensure homogeneity. Ten (10) mL of each solution was sampled into 50 mL falcon tubes on days 0 (immediately after mixing), 7, 14, 21, and 28, and the total phosphorus (P) content, available phosphorus, and pH analyzed. Total P was determined after digestion with 4.4 mL of a digestion mixture (consisting of 350 mL of hydrogen peroxide, 420 mL of sulphuric acid, 14 g of lithium sulfate, and 0.42 g of selenium powder). The dissolved phosphorus in the solution was measured using a spectrophotometer (Shimadzu Model UV-1800), at a wavelength of 882 nm (Murphy and Riley 1962). The available phosphorus was determined by extracting with Olsen's solution and then following the color development using Murphy and Riley's (1962) methods (as described by Okalebo et al., 2002). The pH of the treatments was determined using a glass electrode pH meter (Model H1 110). At the end of the experiment, lemon juice dissolved more phosphorus from the PR than the pineapple juice or distilled water (see result section for details) and was thus used for the subsequent studies.

Table 5.1: Initial characteristics of the organic juices and water used in the dissolution experiment

	Units	Lemon juice	Pineapple juice	Water
pH (H_2O)		2.60±0.11	3.40±0.01	6.90±0.03
Total nitrogen	%	0.13±0.01	0.07±0.04	0.08±0.00
Total phosphorus	%	0.36±0.01	0.37±0.01	0.00±0.00
Available phosphorus	mg L^{-1}	26.72±1.66	4.93±1.10	0.00±0.00
Potassium	mg L^{-1}	642.75±26.05	601.57±13.50	4.31±0.01
Sodium	mg L^{-1}	33.84±11.62	25.99±0.39	0.00±0.00
Magnesium	mg L^{-1}	178.21±3.23	83.30±0.19	1.95±0.00
Calcium	mg L^{-1}	545.30±17.83	211.23±16.80	11.93±0.01

Where: pH (H_2O) = pH in water

5.2.1.2 Preparation of compost with, and without, phosphate rock

Three compost heaps were prepared, from boma manure (i.e., cattle dung mixed with bedding materials from livestock reared under a zero-grazing system), crop residues, and plant materials, following a widespread practice of farmers in the region (Adamtey et al., 2016). The compost was made with the following materials: 250 kg of fresh boma manure, 26 kg of the fresh plant and crop residues (vegetable residues, *Lantana camara* twigs, *Tithonia diversifolia (Tithonia)*) and 70 kg of chopped dry grass materials. In addition, 8.67 kg of PR (with a P content of 2.53% or a total of 1.26 kg P) was added to each of the compost heaps (weighing 346 kg, fresh weight) with the aim of raising the total P content of the compost from 0.34% to 2.87% The first compost heap received PR in powder form (PPR), and the second in dissolved form (DPR), at a ratio of five parts lemon juice to one part PR. A third compost heap was produced using the same materials but without PR. Each compost heap was turned every for three weeks until it reached maturity at 63 days as described by Adamtey et al. (2016).

5.2.2 Assessing the effects of different PR treatments on carrot growth, yield and P use efficiency

5.2.2.1 Treatments, experimental design and management practices

Tables 5.2 to 5.3 show the treatment characteristics and the amount used for the field experimental trials. Nitrogen and phosphorus were applied at a rate of 52.00 kg ha^{-1} N and 40.15 kg ha^{-1} P, based on carrot's N and P requirements (Grubben and Denton, 2004). Eight treatments were studied. These treatments include: dissolved PR composted (DPR composted), dissolved PR applied directly with compost at planting (DPR + compost); composted powdered PR (PPR composted); powdered PR applied directly with compost (PPR + compost); triple superphosphate applied directly with compost (TSP + compost); triple superphosphate applied directly with *Tithonia* (TSP + *Tithonia diversifolia*); compost alone (Compost), and; un-amended soil (Soil) as a control. *Tithonia* was applied as a top dressing, in the DPR composted, PPR composted, and TSP + *Tithonia* treatments 15 days after plant germination to supplement the N requirement levels for carrots (52.00 kg ha^{-1} N) in the long rain season (Table 5.3). Except for the compost alone and un-amended soil treatments, all the treatments received *Tithonia* during the short rain season to supplement N requirements for the crops. Farmers in the area widely use *Tithonia* as a tea or mulch because it is readily available around the farms and has a high N content (Adamtey et al., 2016). Phosphate rock alone was not included as part of the treatments because of its poor performance on crop yields in an earlier study conducted under the SysCom program (unpublished data). The treatments were replicated three times in a Randomized Complete Block Design (RCBD) in split plot arrangement for the two sites. Each experimental plot was 2m × 2m, spaced 1m apart. *Daucus carota* (Carrot seeds (cv. Nantes)) were sown at a rate of 3 seeds per hole with a spacing of 15cm × 7cm. They were later thinned to a single plant per hole, giving a total population of 320 plants per plot. Carrots were selected since they are a root crop of economic importance to farmers in the region (Horticultural Crop Directorate, 2017) and respond well to P fertilizer application (Sanderson and Sanderson, 2007). Compost, powdered, and dissolved PR and TSP were each broadcasted over the entire plot while planting the crop and uniformly spread over the plot by raking-in. At 15 days after germination, fresh *Tithonia* was chopped and applied as mulch in between the plants in the rows as a top-dressing. The experimental plots were regularly weeded and earthed-up mechanically in order to keep them free from weeds and to avoid the roots being directly exposed to sunlight. A total of 600 mm and 1400 mm of supplemental irrigation water was applied at Kianjugu fortnightly during the prolonged hot and dry days without rainfall during the long and short rain season, respectively. The crops at Kangari were solely rain-fed as the rainfall amount received and its distribution over the cropping period was adequate.

Table 5.2: Characteristics of the treatments used for both long and short rain season field experimental trials at Kangari and Kianjugu, Kenya

	Units	Phosphate rock	Compost alone	PPR Composted	DPR Composted	PPR + Compost	DPR + Compost	TSP + Compost	Triple superphosphate	*Tithonia diversifolia*	TSP + *Tithonia*
pH (H_2O)		8.60	7.39	7.50	7.38	NA	NA	NA	5.12	9.71	NA
Total N	%	0.05	1.18	1.19	1.23	1.23	1.36	1.23	0.05	2.81	2.86
Total P	%	14.58	0.41	1.79	1.73	14.99	15.35	20.51	20.10	0.51	20.61
Avail P	mg kg^{-1}	9.40	222.85	239.01	288.46	232.25	258.97	790.17	567.32	283.29	850.61
Potassium	mg kg^{-1}	1010.10	7881.90	6899.10	6719.70	8892.00	9535.50	8365.50	483.60	22600.50	23084.10
Sodium	mg kg^{-1}	2461.00	269.10	243.80	246.10	2730.10	2764.60	2718.60	2449.50	455.40	2904.90
Magnesium	mg kg^{-1}	438.00	981.60	837.60	828.00	1419.60	1598.40	3291.60	2310.00	2709.60	5019.60
Calcium	mg kg^{-1}	672.00	1680.00	1570.00	1600.00	2352.00	2898.00	6990.00	5310.00	18600.00	23910.00
CEC		20.30	37.96	33.57	33.20	NA	NA	NA	57.69	175.51	NA

Total N = total nitrogen; Total P = total phosphorus; Avail P = available phosphorus; CEC = cation exchange capacity; NA = not applicable;

PPR composted = powdered phosphate rock composted with manure and plant residues; DPR composted = dissolved phosphate rock composted with manure and plant residues; DPR + Compost = dissolved phosphate rock applied directly with compost from manure and plant residues; PPR + Compost = powdered phosphate rock applied directly with compost from manure and plant residues; TSP + Compost = triple superphosphate applied directly with compost from manure and plant residues; compost alone = compost from manure and plant residues; TSP + *Tithonia* = triple superphosphate applied directly with *Tithonia*

Table 5.3: Amount of inputs applied (average) per season in the experimental trials at Kangari and Kianjugu, Kenya

Inputs	Amount of compost applied (kg ha^{-1})		Amount of Minjingu Phosphate Rock applied (kg ha^{-1})		Amount of triple superphosphate applied (kg ha^{-1})		Amount of fresh *Tithonia diversifolia* applied (kg ha^{-1})	
	LR	SR	LR	SR	LR	SR	LR	SR
DPR composted	4800	3567	-	-	-	-	4121	5731
PPR composted	4263	3066	-	-	-	-	4451	5999
DPR + compost	9921	7599	172	175	-	-	-	3164
PPR + compost	9921	7599	172	175	-	-	-	3164
TSP + compost	9921	7599	-	-	125	127	-	3164
Compost	26554	20522	-	-	-	-	-	-
TSP +*Tithonia*	-	-	-	-	190	190	9740	9740

Where: LR = long rain season (April to August 2017); SR = short rain season (October 2017 to February 2018); DPR Composted = dissolved phosphate rock composted with manure and plant residues; PPR Composted = powdered phosphate rock composted with manure and plant residues; DPR + Compost = dissolved phosphate rock applied directly with compost from manure and plant residues; PPR + Compost = powdered phosphate rock applied directly with compost from manure and plant residues; TSP + Compost = triple superphosphate applied directly with compost from manure and plant residues; compost alone = compost from manure and plant residues; TSP + *Tithonia* = triple superphosphate applied directly with *Tithonia*

5.2.3 Data collection

Ten plants on each plot were randomly tagged and their height, diameter of the canopy, and the number of leaves measured and counted on the 35th, 51st and 65th days after sowing (DAS) to calculate the exponential increase of foliage and (as a proxy for) the root dry weight of the carrots (Westerveld et al., 2007). The days corresponded to the lag phase, log phase and decelerating phase of carrot growth (Westerveld et al., 2007). The plant height was measured from the collar of the carrot (on the ground) to the tip of the longest leaf, using a ruler. The canopy diameter was measured as the mean of the longest spreading leaves, at a right angle to each other. At harvest (4 months after sowing), the carrots were carefully scooped from the soils and gently cleaned with water. The shoots (the parts above the ground) were separated from the roots (the part below the ground), and the fresh weight yield of all the 320 carrots per plot was weighed using a wash-down scale (model WBW 30aM). Twenty (20) plants from each treatment were randomly selected, and the girth and length of their roots were measured. The root diameter was measured 1 cm below the tip of the shoulder and the root length from the shoulder to the tip of the longest root, in both cases using a stainless steel digital vernier caliper.

5.2.4 Compost and plant tissue analysis

The heaps of mature compost were sampled after 63 days. The samples were air-dried, ground, and then sieved through a 2 mm mesh. The N, P, and K contents of the composts were analyzed after 0.3 g of each compost sample was completely digested with 4.4 mLs of a digestion mixture, as explained in section 2.2.1. Total N was determined by Kjeldahl distillation and titration (as described by Okalebo et al., 2002), phosphorus (as described by Murphy and Riley 1962), and potassium (K) by an Atomic Absorption Spectrophotometer (AAS) (Okalebo et al., 2002). The characteristics of the treatments are shown in Table 5.2. Twenty (20) carrots plants from each treatment were separated into shoots and roots, which were chopped into small pieces, air-dried and oven-dried at 60 ^{o}C for five days to determine the plant dry matter yield and nutrient uptake. The plant dry weight of each sample was measured, after which the samples were finely ground with a milling machine (Model 4 Wiley mill). The N, P and K (NPK) concentrations of the plants were determined in the same way as the concentrations in the different treatments (above). The N, P, and K content of the plant or uptake (see equation 1) was determined following the procedure of Muhmood et al. (2015). Phosphorus recovery efficiency (PRE) and Agronomic P use efficiency (PUE) were then calculated following Zafar et al. (2017) (see equations 4 and 6).

5.2.5 Statistical analysis

Phosphate rock dissolution data were subjected to a normality test using the *dplyr* package. Treatment and seasonal differences in carrot growth, yield, NPK uptake, and PUE data; and juice, volume and time differences in phosphate rock dissolution data were determined by analysis of variance (ANOVA) using the *agricolae* package in R statistical software version 3.3.2 (R Core Team, 2018). A linear mixed-effect model with volume, juice type, and time as fixed factors, was used in the analysis of differences in phosphate rock dissolution data using the *lmer* function in the *lme4* package. Carrot growth, yield, NPK uptake, and PUE data were analyzed using a linear mixed-effect model (with the season and treatment as the fixed factors and replication as the random factor) using the *lmer* function in the *lme4* package. The separation of means was done with Tukey's honest significant difference, using the *cld* function in the *emmeans* package at a 5% level of significance. The relationships between yield parameters and NPK uptake were determined by linear regression analysis using the *lm* function in the *lme4* package at a 5% level of significance (R Core Team, 2018).

5.3 Results

5.3.1 Solubility of phosphate rock in organic citric juices

The results of the solubilization of phosphate rock (PR) in organic juices and water are shown in Figure 5.1a-i. The organic juices and water showed different patterns in the release of available P from PR (Figure 5.1a, d, g). Lemon juice showed a higher release of available P on day 0 (i.e., immediately after mixing), but the available P concentration decreased sharply after that, until day 14, and then gently from day 14 to day 28. With pineapple juice, the available P released increased gently until day 14, and with water, it increased until day 7. After that, the concentration of available P decreased sharply to nearly 0 on day 21 in pineapple juice and on day 14 for water.

In lemon juice, 63% of the total P applied was released into available P (Figure 5.1b) whilst less than 12% and 6% were released in pineapple juice and water, respectively (Figure 5.1e, h). The available P released by the lemon juice was 5 times higher than that released by the pineapple juice and 11 times higher than by water (the control) (both $p < 0.001$). There was an interactive effect of juice type and volume; and juice type and time on P solubilization. In the lemon juice, the available P released in 500 mL (on day 0) at a proportion of 1:5 PR to lemon juice solution was 2 to 26 times higher ($p < 0.001$) than the amount released in 400 to 100 mL (on the same day). The highest concentration of available P constituting to over 50% PR dissolution was released immediately after dissolving (otherwise referred to as day 0). After that, the concentration of available P decreased ($p < 0.001$) over time until day 28. Different volumes of pineapple juice and the distilled water did not have a significant effect on the release of available P from PR in solution (Figure 5.1e, h). There was a negative relationship ($R^2 = 0.44$, $p < 0.001$) between the available P released and the pH of the lemon juice - PR solution, with more available P released at a pH of 3.4 (Figure 5.1 c). The concentration of available P in lemon–PR solution at volume 500 mL decreased significantly ($p < 0.001$) with an increase in pH of the solution from 3.4 to 6.4. Thus, there were discernible patterns observed in the available P concentrations for all the PR juice solutions (Figure 5.1).

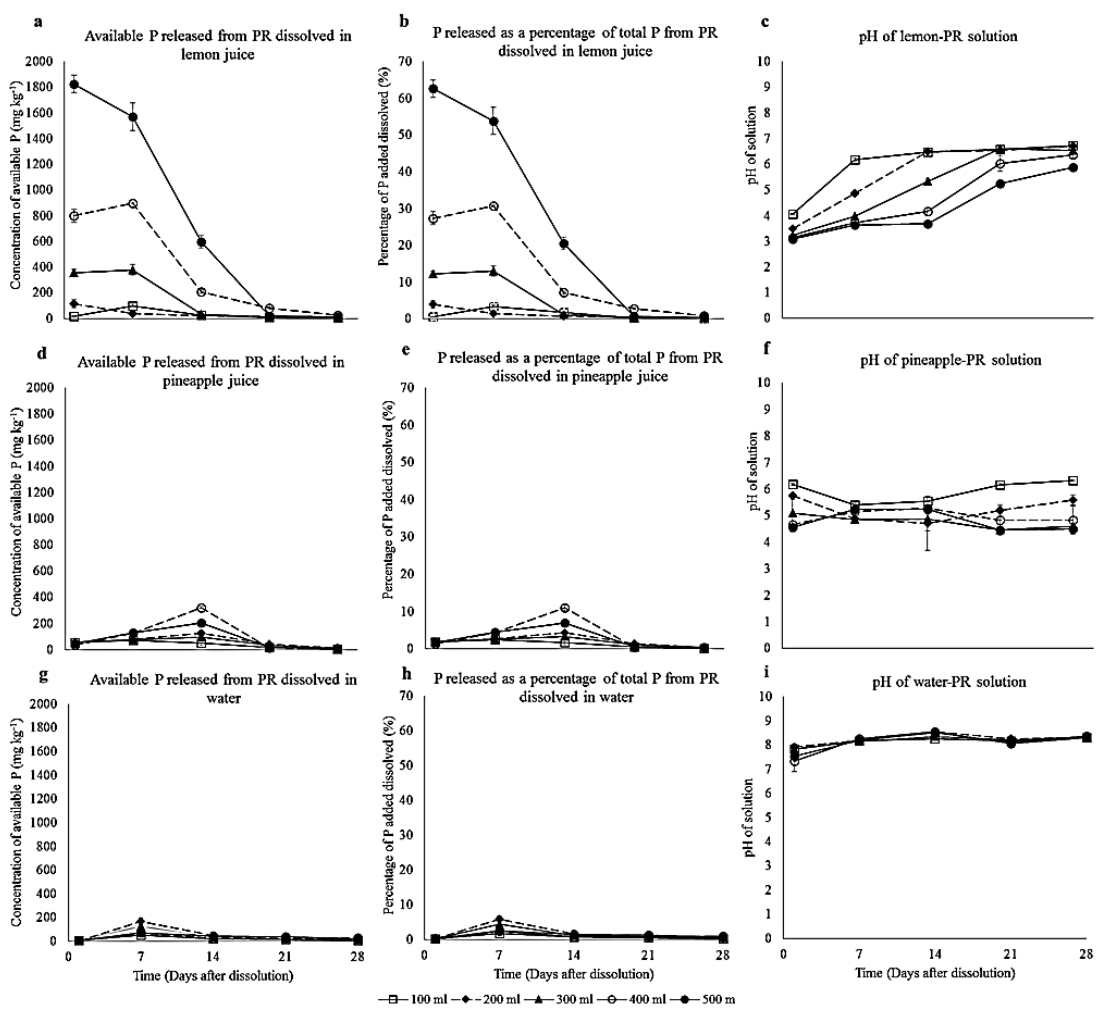

Figure 5.1: Effect of organic juices (lemon and pineapple) and water, and their volume and time on dissolution of phosphate rock to release available phosphorus

Day 0 refers to the time immediately after mixing; PR refers to phosphate rock; and P refers to phosphorus

5.3.2 The effects of different phosphate rock treatments and season on carrot growth and yield

Although significant differences were observed on the different PR treatments on plant growth (number of leaves, canopy diameter, root length, and diameter) and yields (Tables 5.4 and 5.5), the treatments did not show discernible patterns. At both Kangari and Kianjugu sites plant growth (plant height, the number of leaves, canopy diameter, and root) were higher ($p < 0.001$) in the LR season than in the SR season. The DPR + compost treatment gave higher ($p < 0.001$) carrot yields than all the other treatments in Kangari. In both the SR and the LR, DPR + compost gave the highest yield, followed by PPR composted, compost alone, PPR + compost, TSP + compost, TSP + *Tithonia*, DPR composted and, lastly, un-amended soil (Figure 5.2a). In Kianjugu, the performance of the treatments during the long rain season was as follows: DPR composted > DPR + compost ≥ TSP + compost ≥ PPR + compost ≥ compost alone (Figure 5.2b). The short rain season at Kianjugu followed the same pattern except that the DPR + compost was the highest. There were interactive effects of treatment x season ($p < 0.001$) on carrot yields. The yields in the long rain season were 3.3 and 2.8 times higher than the yields in the short rain season at Kangari and Kianjugu, respectively.

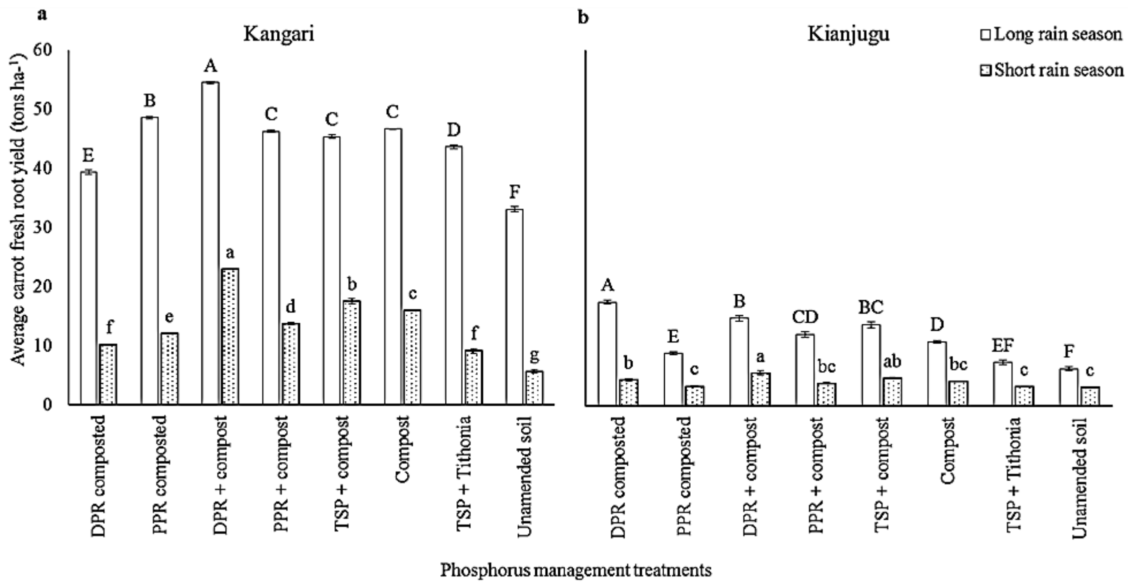

Figure 3.2: Carrot fresh root yields under different PR management in the field trials at Kangari and Kianjugu, Kenya

NB: Different alphabets in capitals (A, B, C, D…) shows significant differences among treatments in long rain season while different alphabets in lower case (a, b, c, d…) shows significant differences among treatments in short rain season

DPR Composted = dissolved phosphate rock composted with manure and plant residues; PPR Composted = powdered phosphate rock composted with manure and plant residues; DPR + Compost = dissolved phosphate rock applied directly with compost from manure and plant residues; PPR + Compost = powdered phosphate rock applied directly with compost from manure and plant residues; TSP + Compost = triple superphosphate applied directly with compost from manure and plant residues; compost alone = compost from manure and plant residues; TSP + *Tithonia* = triple superphosphate applied directly with *Tithonia*

Table 5.4: The effects of different PR management on carrot growth in the field trials at Kangari and Kianjugu, Kenya

Treatment	Plant height (cm)				Number of leaves				Canopy diameter (cm)			
Site	Kangari		Kianjugu		Kangari		Kianjugu		Kangari		Kianjugu	
Season	LR	SR	LR	SR	LR	SR	LR	SR	LR	SR	LR	SR
DPR composted	34.41^{bc}_{A}	13.47^{c}_{B}	38.11^{c}_{A}	25.05^{ab}_{B}	8.40^{ab}_{A}	6.91^{a}_{B}	8.20^{e}_{A}	6.53^{bc}_{B}	13.77^{cd}_{A}	11.05^{e}_{B}	22.33^{ab}	22.16^{a}
PPR composted	33.58^{c}_{A}	18.15^{b}_{B}	34.79^{e}_{A}	23.18^{c}_{B}	8.33^{bc}_{A}	5.87^{e}_{B}	7.67^{f}_{A}	6.20^{d}_{B}	14.33^{bc}	13.41^{bc}	18.40^{g}	19.09^{c}
DPR + compost	35.31^{ab}_{A}	18.41^{b}_{B}	37.14^{cd}_{A}	23.65^{bc}_{B}	7.93^{d}_{A}	6.80^{ab}_{B}	8.40^{cde}_{A}	5.93^{e}_{B}	14.67^{b}	14.77^{a}	19.27^{fg}	19.71^{bc}
PPR + compost	36.55^{a}_{A}	18.11^{b}_{B}	42.99^{a}_{A}	24.83^{bc}_{B}	8.27^{bc}_{A}	5.87^{e}_{B}	8.67^{ab}_{A}	6.47^{c}_{B}	13.21^{d}_{A}	12.08^{d}_{B}	22.49^{abc}_{A}	21.42^{a}_{B}
TSP + compost	36.24^{ab}_{A}	22.57^{a}_{B}	40.01^{b}_{A}	23.86^{bc}_{B}	8.53^{a}_{A}	6.73^{bc}_{B}	8.60^{abc}_{A}	6.53^{bc}_{B}	16.04^{a}_{A}	15.15^{a}_{B}	21.66^{cd}_{A}	19.55^{bc}_{B}
Compost	36.61^{a}_{A}	17.87^{b}_{B}	39.89^{b}_{A}	25.65^{a}_{B}	8.20^{c}_{A}	6.67^{bcd}_{B}	8.80^{a}_{A}	7.40^{a}_{B}	16.25^{a}_{B}	14.15^{b}_{B}	23.42^{a}_{A}	20.35^{b}_{B}
TSP + *Tithonia*	34.07^{bc}_{A}	17.00^{b}_{B}	35.22^{e}_{A}	21.43^{d}_{B}	7.20^{f}_{A}	5.33^{f}_{B}	8.67^{ab}_{A}	5.33^{f}_{B}	13.01^{de}_{A}	11.27^{de}_{B}	21.41^{d}_{A}	16.22^{d}_{B}
Un-amended soil	26.76^{d}_{A}	12.71^{c}_{B}	34.64^{e}_{A}	23.79^{bc}_{B}	7.40^{e}_{A}	5.47^{f}_{B}	8.27^{e}_{A}	6.47^{c}_{B}	10.67^{f}_{A}	9.18^{f}_{B}	20.03^{ef}	19.55^{bc}
Season	34.19^{a}	17.29^{b}	37.85^{a}	23.93^{b}	8.03^{a}	6.21^{b}	8.41^{a}	6.36^{b}	14.00^{a}	12.63^{b}	21.13^{a}	19.76^{b}
Season		***				***				***		
Treatment		***				***				***		
Season x Treatment		***				***				***		

Where: Values followed by different alphabets (a, b, c, d) show significant differences among treatments at (ns; not significant; $*p < 0.05$; $** p < 0.01$, $***p < 0.001$); Mean comparison in for treatments is by column; mean comparison for season is by row;

LR, long rain season; SR, short rain season; DPR Composted = dissolved phosphate rock composted with manure and plant residues; PPR Composted = powdered phosphate rock composted with manure and plant residues; DPR + Compost = dissolved phosphate rock applied directly with compost from manure and plant residues; PPR + Compost = powdered phosphate rock applied directly with compost from manure and plant residues; TSP + Compost = triple superphosphate applied directly with compost from manure and plant residues; compost alone = compost from manure and plant residues; TSP + *Tithonia* = triple superphosphate applied directly with *Tithonia*

Table 5.5: The effects of different PR management on carrot yield parameters in the field trials at Kangari and Kianjugu, Kenya

Treatment	Root length (cm)				Root diameter (cm)			
Site	Kangari		Kianjugu		Kangari		Kianjugu	
Season	LR	SR	LR	SR	LR	SR	LR	SR
DPR composted	19.53[bc]	17.67[cd]	15.61[bcd]	17.61[a]	3.06[b]	1.58[def]	1.92[bc]	1.54[ab]
PPR composted	20.06[ab]	17.36[cde]	13.85[efg]	14.98[efg]	3.06[b]	1.64[bcd]	1.76[d]	1.32[c]
DPR + compost	21.23[a]	19.45[a]	16.97[a]	15.44[def]	3.37[a]	1.93[a]	1.96[b]	1.55[ab]
PPR + compost	19.33[bc]	19.35[a]	16.34[ab]	16.61[abcd]	3.20[b]	1.72[bc]	2.06[b]	1.61[a]
TSP + compost	19.46[bc]	18.30[abc]	15.94[abc]	17.16[abc]	3.14[b]	1.77[b]	2.37[a]	1.49[ab]
Compost	18.96[bcd]	17.98[bcd]	13.31[g]	17.47[ab]	3.20[b]	1.71[bc]	1.76[cd]	1.40[bc]
TSP + *Tithonia*	18.92[bcd]	15.68[f]	13.56[fg]	14.57[fgh]	3.09[b]	1.46[ef]	1.90[b]	1.13[d]
Un-amended Soil	18.02[de]	17.04[de]	12.74[g]	16.43[bcd]	2.76[c]	1.46[ef]	1.58[e]	1.07[d]
Season	19.44[a]	17.85[b]	14.79[b]	16.28[a]	3.11[a]	1.66[b]	1.92[a]	1.39[c]
Season			**			***		
Treatment			***			***		
Season x Treatment			***			***		

Where: Values followed by different alphabets (a, b, c, d) show significant differences among treatments at (ns; not significant; *$p < 0.05$; ** $p < 0.01$, ***$p < 0.001$);

Mean comparison in for treatments is by column; mean comparison for season is by row;

LR, long rain season; SR, short rain season;

DPR Composted = dissolved phosphate rock composted with manure and plant residues; PPR Composted = powdered phosphate rock composted with manure and plant residues; DPR + Compost = dissolved phosphate rock applied directly with compost from manure and plant residues; PPR + Compost = powdered phosphate rock applied directly with compost from manure and plant residues; TSP + Compost = triple superphosphate applied directly with compost from manure and plant residues; compost alone = compost from manure and plant residues; TSP + *Tithonia* = triple superphosphate applied directly with *Tithonia*

5.3.3 The effect of different PR treatments and season on nutrient uptake and P use efficiency

Although there were no discernible patterns in nitrogen (N) uptake among the different treatments, significant differences were observed (Table 5.6), with the un-amended soil, where the nitrogen uptake was significantly lower. An interactive treatment x season effects on N uptake was observed. Between 1.8 and 2.4 times more ($p < 0.001$) N was taken up in the LR season than in the SR season in both Kangari and Kianjugu. The phosphorus uptake from the DPR + compost treatment was similar to the uptake from the TSP + compost treatment (except in the SR season at Kangari) and the PPR + compost (except in the LR season at Kangari) (Table 5.6). The P uptake from the DPR + compost treatment was higher ($p < 0.001$) than the uptake from DPR composted, PPR composted, TSP + *Tithonia*, compost alone (except in the SR season at Kangari) and the un-amended soil. There was an interactive treatment x site, treatment x season, and site x season effect on P uptake. P uptake in the LR season was 1.5 to 1.7 times higher ($p < 0.001$) than in the SR season. Potassium (K) uptake from DPR + compost treatment was similar to the uptake from the PPR + compost, TSP + compost, TSP + *Tithonia* in the LR season at both sites and compost alone treatments (except in the SR season at Kianjugu). The uptake from the DPR + compost was higher ($p < 0.001$) than the uptake from DPR composted (at Kangari), PPR composted (at Kangari and in the SR season at Kianjugu) and the un-amended soil. There was also an interactive treatment x site, treatment x season, and site x season effect on K uptake. K uptake was 1.9 to 2 times higher in the LR season ($p < 0.001$) than in the SR season.

The P recovery efficiency from the DPR + compost treatment was similar to that from the TSP + compost and the PPR + compost at both sites (except in the LR and SR seasons at Kangari, respectively) (Table 5.7). The P use efficiency (PUE) of DPR + compost was highest ($p < 0.001$) in the LR season at Kangari and in both seasons at Kianjugu. In the LR season at Kianjugu, the DPR composted treatment showed a higher ($p < 0.001$) PUE than the other treatments. P recovery and PUE showed an interactive season x treatment effect. P recovery was 10% higher in the LR season than in the SR season, and the PUE was 2.1 times higher in the LR season than in the SR season (both figures $p < 0.001$) at both sites.

Table 5.6: The effects of different PR management on carrot yield parameters in the field trials at Kangari and Kianjugu, Kenya

Treatment	Total N uptake in plants (kg ha^{-1})				Total P uptake in plants (kg ha^{-1})				Total K uptake in plants (kg ha^{-1})			
Site	**Kangari**		**Kianjugu**		**Kangari**		**Kianjugu**		**Kangari**		**Kianjugu**	
Season	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**	**LR**	**SR**
DPR composted	131.85^{a}	66.96^{ab}	87.52^{ab}	50.22^{ab}	28.69^{bc}	14.29^{b}	17.94^{bc}	11.74^{c}	450.67^{b}	213.98^{cd}	332.90^{a}	160.19^{ab}
PPR composted	111.37^{a}	63.38^{ab}	80.95^{ab}	33.27^{bc}	26.93^{cd}	15.67^{b}	17.68^{bc}	8.11^{d}	419.51^{c}	227.78^{bc}	287.09^{ab}	102.37^{bc}
DPR + compost	124.17^{a}	75.66^{a}	92.72^{a}	52.85^{ab}	33.77^{a}	19.06^{a}	21.07^{a}	15.99^{a}	512.94^{a}	290.89^{a}	334.26^{a}	184.67^{a}
PPR + compost	127.98^{a}	81.75^{a}	82.30^{ab}	58.37^{a}	29.82^{b}	19.68^{a}	20.68^{a}	13.96^{ab}	484.77^{ab}	273.09^{ab}	301.98^{a}	202.91^{a}
TSP + compost	114.22^{a}	82.28^{a}	89.78^{a}	51.55^{ab}	33.03^{a}	15.81^{b}	18.84^{ab}	14.34^{ab}	454.34^{abc}	278.64^{ab}	301.08^{a}	160.28^{ab}
Compost	113.06^{a}	67.95^{ab}	64.40^{bc}	50.35^{ab}	26.93^{cd}	18.94^{a}	14.19^{d}	13.47^{bc}	466.98^{abc}	241.71^{abc}	234.20^{bc}	163.75^{a}
TSP + *Tithonia*	113.99^{a}	62.30^{ab}	82.20^{ab}	30.93^{bc}	28.70^{bc}	15.57^{b}	18.15^{bc}	7.63^{de}	464.93^{abc}	194.13^{cd}	284.13^{ab}	92.69^{c}
Un-amended soil	83.15^{b}	46.81^{b}	42.38^{c}	17.95^{c}	18.05^{e}	11.61^{c}	10.92^{e}	5.59^{e}	358.76^{d}	164.17^{d}	190.25^{c}	66.76^{c}
Season	114.98^{a}	68.39^{b}	77.78^{a}	43.19^{b}	28.17^{a}	16.32^{b}	17.43^{a}	11.36^{b}	451.61^{a}	235.55^{b}	283.24^{a}	141.70^{b}
Season		***				***				***		
Treatment		***				***				***		
Season x Treatment		***				***				***		

Where: Values followed by different alphabets (a, b, c, d) show significant differences among treatments at (ns; not significant; *p < 0.05; ** p < 0.01, ***p < 0.001); Mean comparison in for treatments is by column; mean comparison for season is by row;

LR, long rain season; SR, short rain season; DPR Composted = dissolved phosphate rock composted with manure and plant residues; PPR Composted = powdered phosphate rock composted with manure and plant residues; DPR + Compost = dissolved phosphate rock applied directly with compost from manure and plant residues; PPR + Compost = powdered phosphate rock applied directly with compost from manure and plant residues; TSP + Compost = triple superphosphate applied directly compost from manure and plant residues; compost alone = compost from manure and plant residues; TSP + *Tithonia* = triple superphosphate applied directly with *Tithonia*.

Table 5.7: Phosphorus recovery and use efficiency under different PR management in the field trials at Kangari and Kianjugu, Kenya

Treatment	P recovery efficiency (%)				P use efficiency (kg ha^{-1})			
Site	Kangari		Kianjugu		Kangari		Kianjugu	
Season	LR	SR	LR	SR	LR	SR	LR	SR
DPR composted	26.50^{bc}	6.70^{c}	17.47^{b}	15.33^{c}	38.48^{f}	9.98^{f}	17.43^{a}	4.40^{b}
PPR composted	22.20^{cd}	10.13^{bc}	16.80^{b}	6.27^{d}	47.78^{b}	11.89^{e}	8.77^{f}	3.30^{d}
DPR + compost	39.20^{a}	18.57^{a}	25.27^{a}	25.87^{a}	53.72^{a}	22.80^{a}	14.67^{b}	5.55^{a}
PPR + compost	29.33^{b}	20.13^{a}	24.30^{a}	20.83^{abc}	45.33^{c}	13.60^{d}	11.94^{d}	3.76^{cd}
TSP + compost	37.30^{a}	10.47^{bc}	19.73^{ab}	21.80^{ab}	44.54^{d}	17.36^{b}	13.60^{c}	4.67^{b}
Compost	20.67^{d}	18.27^{b}	8.17^{c}	19.63^{bc}	45.86^{c}	15.90^{c}	10.73^{e}	4.08^{bc}
TSP + *Tithonia*	26.50^{bc}	9.63^{bc}	17.97^{b}	5.10^{d}	42.82^{e}	8.97^{g}	7.23^{g}	3.28^{d}
Un-amended soil	-	-	-	-	-	-	-	-
Season	28.82^{a}	13.41^{b}	18.53^{a}	16.40^{b}	45.50^{a}	14.36^{b}	12.05^{a}	4.15^{b}
Season	***				***			
Treatment	***				***			
Season x Treatment	***				***			

Where: Values followed by different alphabets (a, b, c, d) show significant differences among treatments at (ns; not significant; *p < 0.05; ** p < 0.01, ***p < 0.001); Mean comparison in for treatments is by column; mean comparison for season is by row;

LR, long rain season; SR, short rain season;

DPR Composted = dissolved phosphate rock composted with manure and plant residues; PPR Composted = powdered phosphate rock composted with manure and plant residues; DPR + Compost = dissolved phosphate rock applied directly with compost from manure and plant residues; PPR + Compost = powdered phosphate rock applied directly with compost from manure and plant residues; TSP + Compost = triple superphosphate applied directly with compost from manure and plant residues; compost alone = compost from manure and plant residues; TSP + *Tithonia* = triple superphosphate applied directly with *Tithonia*.

5.4 Discussion

5.4.1 The solubility of phosphate rock in organic juice

The use of locally available organic juices to solubilize PR has the advantage of offering an alternative means of improving PR fertilizer use in acidic soils and is of particular relevance for small scale, organic and ecological farming; thus it is important to assess their efficiency. The study showed lemon juice to be more effective than pineapple juice or water in solubilizing PR to release available P (Figure 5.1). This can be attributed to the higher available P concentration and organic acids effect. Lemon juice contains more available P (26.7 mg L^{-1}) than pineapple juice (4.9 mg L^{-1}) and water (0 mg L^{-1}) and increased the concentration of P released from PR. Secondly, lemon juice contains over 77.8 g L^{-1} of organic acids (e.g., citric, lactic, malic, ascorbic, oxalic and tartaric acids) with a concentration of citric acid of around 73.9 g L^{-1} (Nour et al., 2010). By contrast, pineapple juice contains only 5.1 g L^{-1} organic acids (citric, malic, and quinic acid) and has a concentration of citric acid of around 3.3 g L^{-1} (Xin-Hua et al., 2014). Chien et al. (2010) and Osman (2015) argue that the abundance of hydrogen ions (i.e., organic acids) in lemon juice could chelate the rock and the minerals within it to form cation-organic complexes on the mineral's surfaces. This could cause a shift of electron density towards the framework of the mineral, increase the electron density of the cation-oxygen bonds, and make them more susceptible to hydrolysis. In addition, the citric acid could also have a strong effect on the solubilization of PR (Ca_{10} $(PO_4)6F_2$) through the substitution of Ca^{2-} and F^- ions to form available P ($H_2PO_4^-$) (see equation 11) (Osman, 2015). These are all viable explanations as to why lemon juice had more effect on the solubility of PR and the extraction of P than pineapple juice or water.

$$Ca_{10}\,(PO_4)_6F_{2\,+}\,12H^+ = 10Ca + 6H_2PO_4^- + 2\,F \qquad \text{Eq. 11}$$

The regression analysis showed the importance of pH of a medium in accounting for 44% of PR solubilization to release available P. A low pH (≤ 3.4), as in the case of lemon juice, enhanced PR solubilization, as also reported by Kumari and Phogat (2008). A moderate pH (5.5–6.5) slowed the solubilization of PR (Jamal et al., 2018). This may explain the high available P measured on day 0 (immediately after mixing) in the lemon juice and its subsequent decline throughout the experimental period.

It was also observed that an increase in the ratio of lemon juice to PR corresponded with an increase in available P release in the solution, with 500 mL of lemon juice (ratio of 1:5 PR to lemon juice) causing the highest available P release (Figure 5.1). This could be attributed to the addition of available P from the juice (as explained earlier) and increased availability of H^+ ions in citric acid, which might have caused the chelation of P binding cations in PR (Osman 2015). This result is in line with existing literature where, in liquid interphase at constant pressure, an increase in the volume of the dissolving solution increases intermolecular mobility and the contact of ephemeral molecules, which is particularly associated with the hydrogen bonds without the solvent matrix breakage (Ruelle, 1999). Furthermore an increase in dissolution volume increases the ion equilibrium effect, enhancing more solubilization of the ephemeral molecules before equilibrium is attained. Our observation is also in line with the findings of Ivanova et al. (2006), who reported that the ratio of PR solid material to the volume of dissolving solution is one of the critical elements in enhancing P release. By contrast, an increase in the volume of pineapple juice had no effect on P release, implying that the juice had fewer H^+ ions groups for chelation P binding cations in PR.

The length of time of dissolution is critical in determining the efficiency of organic juice in solubilizing PR to release available P (Ivanova et al., 2006). The study found that the highest concentration of available P was released in lemon juice on day 0 (immediately after mixing), which could be due to the lower pH of the solution (Figure 5.1). The release of available P from PR mixed with industrial citric, oxalic, and gluconic acids has been found to increase significantly from the time of dissolution up to two hours (Ivanova et al., 2006). Beyond two hours after dissolution, the amount of available P in solution was found to decreases over time. The lemon juice showed a similar trend and provides a suitable alternative to the use of industrial acids. By contrast, pineapple juice and water showed a gradual increase in available P to day 14 and 7 respectively, followed by a gradual decrease. This gradual increase in available P can be attributed to presence of dissociated hydrogen ions in the PR-pineapple juice or water although at low concentrations. The pH for the PR-lemon juice solution changed from acidic to moderately acidic over time (from day 0 to 28), which corresponded to a decrease in the available P in the PR-lemon juice solution (Figure 5.1). At high pH levels, P is precipitated by calcium (Ca) in the PR solution (Roy et al., 2018), which can convert the available P in solution to a non-available form. The interactive effect of the juice type and volume, juice type and time on P solubilization indicates that the type and volume of juice (in the case of lemon juice), as well as the time taken for the PR to remain in the juice are critical in determining PR solubility.

At the current level of vegetable production (0.0056 to 0.012 ha per farm) in the Muranga County (unpublished data from a survey conducted in 2017 by FiBL), about 8 to 16 L of lemon juice would be required by a farmer to dissolve the PR needed to grow carrots and other vegetables. In our study, 20 lemon fruits produced a liter of lemon juice on average implying that a farmer in Murang'a would require about 160 to 320 lemon fruits (based on the current farm sizes) to dissolve the PR needed for vegetable production. According to Rattanpal et al. (2017) a lemon tree, on average, produces 1680 fruits per season (which translates into 84 L of lemon juice at our level of juice extraction). Thus, the use of lemon juice to dissolve PR seems feasible and practicable in Muranga, considering that nearly 39% out of 292 farmers owned at least one lemon tree and some as many as six (unpublished data from a 2017 survey conducted by FiBL). Extrapolation shows that as many as 16 lemon trees would be required to produce 27,540 lemon fruits in order to extract the 1377 L of lemon juice required to dissolve 275 kg of PR to grow a hectare of carrots. This implies that where smallholder farmers have access to more land, the lemon juice technology could be targeted for use in high value crops, which are often grown on smaller areas in order to ensure efficient production and a sustainable supply. This could, in turn, provide a potential opportunity to further exploit lemons, which are often underutilized by households, for triggering public-private partnerships in lemon-based local start-up businesses around the lemon technology (including the possible use of the peels) and its potential benefits to rural women and youth (who are often at a disadvantage).

5.4.2 The effects of PR treatments on carrot yield, nutrient uptake, and P use efficiency

The DPR + compost treatment was more effective than the other treatments in increasing the yield of carrots, and led to significantly higher P-recovery and use efficiency (Figure 5.2; Table 5.4, 5.5, 5.6 and 5.7). The higher root yields in DPR + compost at Kangari, DPR composted in the long rain (LR) season and DPR + compost in the short rain (SR) season at Kianjugu can be attributed to greater availability of P as there is a positive relationship ($p < 0.01, 0.05$) between available P from inputs and P uptake. Dissolving PR in lemon juice, which contains a high proportion of citric acid, can increase the availability of P in soils, mainly through increasing the solubilization of P compounds and decreasing the adsorption of P (Bolan et al., 1994). Traina et al. (1986) identified three possible mechanisms that could explain the effect of organic acids (such as the lemon juice) on P adsorption: (i) the dissolution of adsorbents; (ii) competition for P adsorption sites; and (iii) changes in the surface charge of adsorbents. Organic acids dissolve P adsorbent metal ions in the soil (Fe, Al, and Ca) into solution media through acidification and complex formations between the anions, i.e., carboxyl (-COOH) and phenolic (-OH) functional groups from the organic acids and the metal ions (Adeleke et al., 2017). Competition for P adsorption sites then occurs through ionic exchange between the anions in the organic acids (–COOH and -OH functional groups) and the orthophosphate bound in the solid solution interface as a result of high and preferential affinity of functional groups compared to orthophosphate (Dorozhkin, 2012). These anions adhere to the adsorbents' surfaces, extracting phosphate ions through electron transfer or breakdown of oxygen links within the metal complexes, changing the surface charge on the adsorbents. Yadav et al. (2017) also reported that the application of dissolved PR increases plant P uptake and crop yields. The low availability of P, P recovery, and use efficiency in the PPR + compost treatment is an indication that the direct application of powdered PR (with or without compost) was not as efficient as dissolving PR in lemon juice and applying it directly with compost. Similarly, the higher yields, P recovery and use efficiencies in the TSP + compost treatment, in comparison to the TSP + Tithonia treatment, indicates that compost also had an influence on crop P recovery efficiency from the soil due to presence of the carboxylic and hydroxyl groups in the organic matter, and that its use in combination with mineral fertilizer can support sustainable crop production (Zafar et al., 2017).

Weather (rainfall amount and distribution, temperature, etc.) and soil characteristics are among the environmental factors that affect crop yields, nutrient uptake, and use efficiency (Brouder and Volenec, 2008). In this study, there was higher nutrient (NPK) uptake, P recovery, and use efficiency and crop yields in the LR season than in the SR season (Figure 5.2; Table 5.4, 5.5, 5.6 and 5.7). This can mainly be attributed to increased precipitation (Figure 3.2) and subsequent increase in soil moisture which enhanced nutrient availability and transport to the roots (through mass flow) and uptake by the plants (Etienne et al., 2018; Syers et al., 2008). Jeptoo et al. (2013) found that carrots grown in a LR season, which received 328.8 mm rainfall, had more leaves, larger canopies, were taller, had greater root volume, and higher total yields than those grown in a SR season (with 228.4 mm rainfall). Besides the amount of rainfall, temperature differences between the two seasons may have contributed significantly to the observed difference. The SR seasons in Kenya are characterized by higher temperatures than the LR season and are coupled with prolonged dry periods (Adamtey et al., 2016). High temperatures can cause heat stress in the root zone which can affect nutrient availability, transport, assimilation, and metabolism within the plants (Giri et al., 2017).

The site at Kianjugu is at a lower altitude (1328 m ASL) with warmer temperatures (26-30^{o} C) than the site at Kangari (section 3.1). The warmer conditions would have increased metabolic activity and the ability of the crop to obtain and utilize assimilates for vegetative growth (Lafta and Lorenzen, 1995) at the expense of yields. This may partly explain the higher plant height, number of leaves, and canopy diameter and smaller carrot diameter and low yields observed at Kianjugu. The lower carrot yields observed at Kianjugu can be attributed to the effects of higher temperature as discussed above and the inherent soil characteristics at the site, which are sandy-clay soils with a high bulk density, relatively low available P, total nitrogen and soil organic carbon (Table 4.1), which limited the development and penetration of the roots. Kangari site is at a higher altitude (2134 m ASL and has lower temperatures, of 15-22°C). The site had shorter carrots with a smaller canopy diameter and fewer leaves at 65th DAS, although the carrots had longer roots, larger root diameters, and higher yield. Lower vegetative growth at Kangari can be attributed to a lower rate of metabolic activity, acquisition, and the utilization of assimilates as a result of cooler climatic conditions, whilst the increased carrot root yields can be explained by the soil's texture and higher fertility. The soil at Kangari is loam, which is more friable, with lower bulk density and higher levels of available P, total nitrogen, and soil organic carbon (Table 4.1), which would enhance root development and facilitate penetration (Mbatha et al., 2014).

5.5 Conclusion

The study provides interesting insights into options for phosphate rock management and phosphorus utilization in vegetable production in Kenya and other parts of SSA. Our findings built upon the phosphate rock acidulation technology by identifying that not all organic materials can effectively be used in phosphate rock dissolution, and that the volume of juice (in the case of lemon), as well as the time that phosphate rock remains in organic juices, are critical in determining its solubility.

The study further revealed that in the given environment the forms in which phosphate rock is applied can affect crop nutrient uptake, phosphorus recovery and use efficiency. Phosphate rock dissolved in lemon juice, when applied together with compost at planting, can significantly increase phosphorus and potassium uptake, phosphorus recovery and crop yields. This implies that small-scale farmers can offset the phosphorus deficiency that commonly occurs in their farms (especially in organic farming). However applying such a system to high value crops in large-scale crop production, could raise challenges in terms of the availability and costs of lemon. Decision makers could consider developing public-private partnerships to target the technology to make it more technically and economically feasible and therefore sustainable.

CHAPTER SIX.

GENERAL DISCUSSION AND RECOMMENDATION

6.1 General Discussion

The study has demonstrated that soils possess different capacities of binding and fixing added phosphorus from fertilizer inputs with calcium, iron, aluminum, soil organic carbon, cation exchange capacity, kaolinite and gibbsite playing a significant influence in phosphorus sorption in soils studied. The positive and significant relationship between calcium and adsorption maxima attest to previous reports that high soil pH above 5.5 could increase the affinity of calcium for phosphorous sorption (Baker et al., 2013; Pagliari et al., 2017). On the other hand, the negative relationship between adsorption maxima and soil organic carbon implies that organic matter can inhibit adsorption of phosphorus to surface clay minerals (Hunt et al., 2007) through the various mechanisms (Muindi et al., 2017) including: (i) Adherence of large, humic molecules to sorbing surfaces that mask adsorption sites and prevent them from interacting with phosphorous ions; (ii) Organic acids produced by plants roots and microbial decay can also serve as organic anions, which compete with phosphorous ions or positively charged sites on the surface of clays and hydrous oxides; or (iii) Certain organic compounds can entrap reactive Al and Fe in stable organic complexes called chelates and once chelated, the metals are unavailable for reaction with phosphorous ions in the soil solution. This highlights the importance of organic farming as a sustainable production system to improve phosphorus availability in the soils. The decrease in adsorption maxima with increase in pH can be attributed to increased electrostatic repulsion of phosphate ions caused by increased negative surface charges as pH increases (Haynes, 1982); competition between hydroxyl (OH-) and phosphate ions for sorption sites on mineral surfaces as pH increases (Haynes, 1982); or neutralization of sites where more reactive Al surfaces were once present by aluminum hydroxides polymers as pH increases (Muindi, et al., 2017). The pH of the soils (both solid and liquid matrices) can also affect protonation and deprotonation of functional groups and surface binding sites (Sims and Pierzynski, 2005). These effects alter the electronegativity of the surfaces of soil particles; a relationship commonly referred to as the adsorption envelope (Sims and Pierzynski, 2005, Muindi et al., 2017). Soils dominated by goethite [α-FeO(OH] and gibbsite [Al $(OH)_3$], as are the soils in Chuka, Kangari and Thika, are particularly susceptible to each of the above-named phosphate adsorption mechanisms and relationship (Tisdale et al., 2002; Muindi et al., 2017). Application of compost or lime can reduce phosphorus adsorption in such soils and could improve P availability. The differences in the standard phosphorus requirement as a result of different binding capacity suggest that blanket application of phosphorus fertilizer rates for all the study sites is not viable.

Locally available organic juices have demonstrated the capacity of dissolving phosphate rock, improving nutrient uptake and yields. Use of lemon juice with low pH and high citric acid level is more effective in enhancing high phosphorus release from phosphate rock fertilizer. Citric acid has the highest value of dissociation constant, pKa (4.13), compared to other organic acids such as gluconic (pKa = 3.6) and oxalic acid (pKa = 1.06) (Osman, 2015). According to Chien et al. (2010) and Osman (2015), high hydrogen ions presence in lemon juice increases the surface area for phosphate rock and other minerals chelation resulting to formation of cation-organic complexes with oxalic acid, which has the OH-1 and COOH-1 group in the ortho position. As a result the chemisorption of the cation-organic complexes on the mineral’s surfaces causes a shift of electron density towards the frame work of the mineral. Through the processes of competition for adsorption sites, dissolution of adsorbents and change on adsorbent surface charges, the organic acids effectively enhances solubilization of phosphate rock releasing phosphorus for plant uptake. Application of phosphate rock immediately after dissolving with lemon juice and compost resulting in increased supply of phosphorus, high phosphorus recovery and use efficiency. This is of relevance to small-scale farmers who can use locally available organic sludge with a low pH to improve the availability of P from PR for crop production. Besides, use of these materials has capacity of improving the soil fertility (Appendix 1) (Adamtey et al. unpublished data).

6.2 Recommendation

The study recommends that:

- To improve P availability on Humic andosols, Humic nitisols, Rhodic nitisols and Orthic acrisols soils, organic matter (e.g compost and manure) and lime could be used during cultivation. There is the need to increase the soils sample size to cover the different counties in the central highlands of Kenya in order to be resolute with the factors responsible for the phosphorus sorption – a prerequisite to developing efficient measures to improve phosphorus availability for crop use. To grow crops such as banana (*Musa paradisiacal*), maize (*Zea mays*), taro (*Colocasia esculenta*), cowpea (*Vigna unguiculata*), sweet potato (*Ipomea batatas*), Irish potato (*Solanum tuberosum*), Chinese cabbage (*Brassica oleracea*), eggplant (*Solanum melongena*), millet (*Pennisetum glaucum*), soybean (*Glycine max*) and tomato (*Lycopersicon esculentum*) and carrots (*Daucas carota*) we recommend the following phosphorus application rates for the different soils. Humic andosols (413 to 416 kg ha^{-1}), Humic nitisols (402 to 485 kg ha^{-1}); Rhodic nitisols (402 to 403 kg ha^{-1}) and Orthic acrisols (161 to 162 kg ha^{-1}).
- Further studies should be conducted to explore the possibility of using other acidic organic materials in the dissolution of phosphate rock. Besides the studies should be conducted to examine the mechanisms through which the different acids in organic materials solubilize phosphate rock, adsorb phosphate in soils, and make the phosphorus soluble and available for plant uptake.
- Finally, introduction of such lemon technology could encourage farmers to plant more lemon trees around their farms, which can serve as alternative sources of income especially in the current era of COVID-19 where the demand for lemon has greatly increased, as well as improving the environment and ecosystem services (by providing more shade, habitat for pollinators etc.). There is need to assess the practical and economic feasibility of using lemon juice technology in large scale crop production.

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APPENDICES

Appendix 1: Soil chemical characteristics after cropping season at Kangari and Kianjugu

	pH	SOC	Nitrogen	Potassium	Sodium	Magnesium	Calcium	CEC	Al^{3+}	Iron	Zinc	Manganese
	H_2O	%	%	$\mu g\ g^{-1}$	$\mu g\ g^{-1}$	$\mu g\ g^{-1}$	$\mu g\ g^{-1}$	$meq100g^{-1}$	%	$\mu g\ g^{-1}$	$\mu g\ g^{-1}$	$\mu g\ g^{-1}$
Nutrient source						**Kangari site**						
DPR composted	5.04^{ab}	2.79	0.79	214.54^{b}	80.71^{cd}	273.03^{ab}	977.24	8.06	0.78	127.24	15.65	91.49
PPR composted	5.33^{a}	2.65	0.83	255.40^{ab}	84.46^{bcd}	245.61^{ab}	1002.62	8.08	0.77	130.82	20.87	120.92
DPR + compost	5.32^{a}	3.13	0.92	260.51^{a}	124.50^{a}	289.47^{a}	863.02	7.94	0.79	172.04	22.07	147.18
PPR + compost	5.33^{a}	2.79	0.82	233.69^{b}	117.62^{ab}	265.35^{ab}	939.16	8.02	0.82	150.54	16.36	108.99
TSP + compost	5.12^{ab}	3.00	0.85	233.69^{b}	110.74^{abc}	206.69^{bc}	939.16	7.50	0.79	175.63	18.30	128.08
Compost	5.14^{ab}	2.94	0.67	245.19^{ab}	127.63^{a}	235.75^{abc}	977.24	8.03	0.80	159.50	18.21	129.67
TSP + Tithonia	5.25^{a}	3.00	0.84	219.65^{b}	81.96^{cd}	269.19^{ab}	913.78	7.73	0.81	161.29	19.45	97.85
Un-amended soil	4.75^{b}	2.68	0.79	146.86^{c}	50.05^{d}	155.70^{c}	1053.39	7.16	0.88	145.16	15.06	92.28
						Kianjugu site						
DPR composted	5.64	0.82	0.99	247.74^{ab}	72.57^{a}	427.08	1129.53	10.16	0.00	145.16	15.68	829.75
PPR composted	5.73	0.73	0.89	257.96^{a}	67.57^{ab}	408.99	1015.31	9.44	0.00	118.28	13.62	797.14
DPR + compost	5.87	0.74	0.89	237.53^{bc}	56.31^{b}	406.25	1015.31	9.32	0.00	152.33	16.27	857.60
PPR + compost	5.76	0.69	0.91	241.36^{b}	59.43^{b}	403.51	1002.62	9.25	0.00	120.07	14.80	861.58
TSP + compost	5.73	0.60	0.97	247.74^{ab}	46.92^{c}	378.84	989.93	8.95	0.00	111.11	11.70	767.70
Compost	5.54	0.58	0.90	236.25^{bc}	43.17^{c}	383.77	1015.31	9.07	0.00	107.53	12.64	739.06
TSP + Tithonia	5.49	0.73	0.91	250.30^{a}	57.56^{b}	426.54	1051.31	9.52	0.00	111.11	12.70	785.20
Un-amended soil	5.49	0.66	0.91	233.69^{c}	53.80^{bc}	345.94	951.86	8.48	0.00	107.53	14.06	832.94
Treatment	*	ns	ns	**	**	*	ns	ns	ns	ns	ns	ns

Source: Adamtey et al. unpublished data

SOC = soil organic carbon; Al^{3+} = Exchange aluminium

Values followed by different alphabets (a, b, c, d) show significant differences among treatments at (ns; not significant; *$p < 0.05$; ** $p < 0.01$); Mean comparison for treatments is by column;

DPR Composted = dissolved phosphate rock composted with manure and plant residues; PPR Composted = powdered phosphate rock composted with manure and plant residues; DPR + Compost = dissolved phosphate rock applied directly with compost from manure and plant residues; PPR + Compost = powdered phosphate rock applied directly with compost from manure and plant residues; TSP + Compost = Triple superphosphate applied directly compost from manure and plant residues; compost alone = compost from manure and plant residues; TSP + *Tithonia* = Triple superphosphate applied directly with *Tithonia diversifolia*.