

**EFFECT OF TITHONIA BIOMASS AND MINERAL FERTILIZER APPLICATION
ON SOYBEAN PERFORMANCE IN DEGRADED TECHNOSOLS FROM
TANTALUM MINING IN GATUMBA, RWANDA**

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DECLARATION

Candidate's declaration

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

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DEDICATION

This thesis is dedicated to my loving God.

I also dedicate this thesis to my family and my fiancé Uwera Vivine who have been a great source of motivation and inspiration.

Finally, this thesis is dedicated to all those who believe in the richness of learning.

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TABLE OF CONTENTS

DECLARATION	i
DEDICATION.....	ii
ACKNOWLEDGEMENTS.....	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	viii
LIST OF FIGURES	x
LIST OF ABBREVIATIONS AND ACRONYMS	xii
ABSTRACT	xiii
CHAPTER 1	1
INTRODUCTION	1
1.1 Background of the study.....	1
1.2 Statement of the problem.....	3
1.3 Research objectives	3
1.4 Research hypothesis	4
1.5 Justification of the study.....	4
CHAPTER 2.....	6
LITERATURE REVIEW.....	6
2.1 Introduction.....	6
2.2 Coltan Mining	6
2.3 Agricultural productivity of Rwanda	8
2.4 Background of soybean production in Rwanda	9
2.5 Restitution and recultivation of coltan mining wasteland in Rwanda.....	10
2.6 Role of legumes in biological nitrogen fixation.....	11

2.7 Combining inorganic and organic nutrient sources (tithonia) for soil fertility replenishment.....	12
2.8 Phosphorus sorption by soils	14
2.9 Matongo rock phosphate versus mijingu rock phosphate in replenishing soil P	15
2.10 Improving rock phosphate solubility.....	16
CHAPTER 3.....	18
3.0 MATERIALS AND METHODS.....	18
3.1 Study area description	18
3.2 Establishment of greenhouse experiment	19
3.3 Establishment of field experiment.....	21
3.4 Soil sampling.....	22
3.5. Sampling and measurement of organic materials	23
3.5.1 Soybean plant height and number of pods	24
3.5.2 Soybean harvest.....	25
3. 6 Laboratory analysis	25
3.6.1 Soil analyses.....	25
3.6.1.1 Soil pH	26
3.6.1.2 Total nitrogen	26
3.6.1.3 Available phosphorus.....	27
3.6.1.4 Exchangeable K, Ca, Mg, Na and cation exchange capacity	27
3.6.1.5 Organic carbon.....	28
3.6.1.7 Soil particle size analysis	29
3.6.2 Plant tissue analyses for N, P and K.....	29
3.7 Secondary data collection	30
CHAPTER 4.....	32

RESULTS AND DISCUSSION.....	32
4.0 An overview of the results presentation and discussion.....	32
4.1 Soil properties and as affected by various treatments	32
4.1.1 Soil properties in the greenhouse experiment	32
4.1.2 Soil properties in the field experiment.....	37
4.2 Response of Soybean performance to various experimental treatments	42
4.2.1 Soybean growth performance in the Greenhouse and in the Field	42
4.2.2 Soybean plant height	43
The results for soybean plant heights in the greenhouse (January 2012) and field experiments during the 2011 SR are presented in Figures 5 and 6. Figure 5 presents Greenhouse soybean heights while Figure 6 presents field heights.....	43
4.2.3 Soybean number of pods and nodules	45
4.2.4 Soybean shoot dry matter yield.....	48
4.2.6 Soybean root dry matter.....	50
4.2.7 Soybean grain yield	52
4.3 Nutrients uptake by soybean.....	55
4.3.1 Nutrients accumulation by soybean in the greenhouse experiment	55
4.3.2 Soybean nutrient accumulation in the field experiment	57
4.3.3 Nitrogen accumulation by soybean at maturity stage in both greenhouse and field experiments.....	60
4.3.4 Phosphorus accumulation by soybean at maturity stage in both greenhouse and field experiment	61
4.3.5 Potassium accumulation by soybean at maturity stage in both greenhouse and field experiments.....	62
CHAPTER 5.....	63

CONCLUSION AND RECOMMENDATIONS	63
5.1 Conclusions	63
5.2 Recommendations	64
REFERENCES	66
APPENDICES	78

LIST OF TABLES

Table 1: The greenhouse experimental treatments for organic and mineral inputs.....	21
Table 2: The field experimental treatments for organic and mineral inputs	22
Table 3: Chemical properties of <i>Tithonia diversifolia</i> leaves (T), matongo rock phosphate (MtRP), minjingu rock phosphate (MRP), triple super phosphate (TSP) and ammonium sulphate (AS)	24
Table 4: Soil chemical and physical properties at the beginning of the Greenhouse experiment (January 2012)	33
Table 5: Effect of tithonia green biomass and mineral fertilizers on soil properties at the end of the greenhouse experiment (April 2012) at the National University of Rwanda	34
Table 6: Changes in soil chemical properties after the greenhouse experiment at the National University of Rwanda	35
Table 7: Soil chemical and physical properties at the beginning of the field experiment (September 2011) at Gatumba Mining District	38
Table 8: Effect of tithonia green biomass and mineral fertilizers on soil properties at the end of the field experiment at Gatumba Mining District	39
Table 9: Changes in soil chemical properties after the field experiment in Gatumba Mining District	42
Table 10. Soybean number of pods and nodules per plan in the greenhouse at NUR.....	46
Table 11. Soybean number of pods and nodules per plant in the field during the 2011 short rains season.....	47
Table 12: Above ground (AG) soybean plant and root biomass nutrient accumulation at harvest in the greenhouse experiment	56
Table 13: Soybean grain and shoot nutrient accumulation at harvest during 2011 short rain in the field experiment	58

Table 14: Soybean above ground (AG) and root nutrient accumulation at harvest during 2011
short rain in the field experiment 59

LIST OF FIGURES

Figure 1: Agricultural zones and national parks of Rwanda (Verdoot and van Ranst, 2003)...	8
Figure 2: Location of the investigation area Gatumba Mining District (red circle), Rwanda (Paulmann, 2012).....	18
Figure 3: Rainfall amount during 2011 short rain (September to December 2011) at Gatumba Mining District, Rwanda (Measured with Davis weather station installed on the experimental site).....	19
Figure 4. Relationship between pH changes and P availability in pegmatite and mixture substrates	36
Figure 5: Soybean plant height at harvest in the Greenhouse during the 2011 short rains season	44
Figure 6: Soybean plant height at harvest in the field during the 2011 short rains season	45
Figure 7: Soybean shoot dry matter at harvest in the greenhouse	49
Figure 8: Soybean shoot dry matter at harvest in the field experiment during the 2011 short rains season.....	50
Figure 9: Soybean root dry matter at harvest in the greenhouse	51
Figure 10: Soybean root dry matter at harvest in the field experiment during the 2011 short rains season.....	52
Figure 11: Soybean grain yield at harvest in the greenhouse	53
Figure 12: Soybean grain yield at harvest in the field experiment during the 2011 short rains season	54

LIST OF APPENDICES

Appendix 1: Field experimental layout	78
Appendix 2: Calculations	79
Appendix 3: Summary of soil chemical data interpretation.....	80
Appendix 4: Soybean plants sown in large containers in the greenhouse	81
Appendix 5: Clay mineral contents in B horizons of soils from Gatumba mining district	82

LIST OF ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
AS	Ammonium Sulphate
CRD	Complete Randomized Design
DM	Dry Matter
GMC	Gatumba Mining Concession
GMD	Gatumba Mining District
INEAC	Institut National pour l'Étude Agronomique du Congo Belge
ISFM	Integrated Soil Fertility Management
LSD	Least Significant Difference
MRP	Minjingu Rock Phosphate
MtRP	Matongo Rock Phosphate
N KCl	Normal Potassium Chloride
RAE	Relative Agronomic Effectiveness
RGMA	Rwanda Geology and Mine Authority
RSG	Reference Soil Group
SOM	Soil Organic Matter
TSP	Triple Superphosphate
WRB	World Reference Base for Soil Resources

ABSTRACT

Large areas of the Gatumba Mining District (GMD) in Rwanda are covered by Technosols (pegmatite or pegmatite-soil mixtures) resulting from coltan mining activities. These substrates are poor in soil plant nutrient contents and are low in soil productivity. Due to agricultural land shortage in Rwanda, almost all the available land is farmed. The present study was conducted to evaluate the effect of tithonia and inorganic fertilizers on plant nutrient uptake and biomass production of soybean grown in Gatumba soils that are affected by the previous coltan mining activities. A greenhouse pot experiment and a field trial were conducted using pegmatite substrate alone and pegmatite-Lixisol B_t mixture in a completely randomized design (CRD). Another experiment was set on cambisol in a farmer's field to compare the treatments from the technosols (affected by mining). Tithonia biomass (T) was applied at 5 tonnes (t) dry matter (DM) ha⁻¹ alone and combined with triple superphosphate (TSP), Matongo rock phosphate (MtRP) (for the greenhouse), Minjingu rock phosphate (for the field trials) and ammonium sulphate (AS). Soybean biomass, grain yield as well as its total N, P and K were measured at harvest while soil total nitrogen (N), available phosphorus (P), potassium (K) and carbon (C) were analyzed before and after the trials. The results demonstrate that soybean DM, grain yield, N, P and K accumulation were higher on pegmatite than on the mixture, The combination of T, MtRP and TSP also gave higher grain yields on both pegmatite (2.1t ha⁻¹) and mixture (1.7 t ha⁻¹) in the greenhouse. In the field, T+MRP and AS treatments, compared to other treatments, gave highest grain yields (1.5 ha⁻¹) followed closely by T+MRP+TSP (1.49ha⁻¹) on pegmatite while on the mixture, T+MRP+AS gave highest grain yields (0.87 ha⁻¹) followed closely by T+MRP+TSP (0.7 ha⁻¹). At the end of the greenhouse experiment, all treatments on both pegmatite and the mixture showed a general increase in pH, total N, exchangeable K and total organic C with the exception of the available P in the mixture which had declined. The same increase in soil nutrients was observed also in the field trial with the exception of total N that declined in all soil types and treatments. The combination of tithonia green manure and different inorganic fertilizers significantly (<0.05) increased the N, P and K accumulation of soybean grain, shoot and root biomass over tithonia alone. The results indicate that soil plant nutrients generally increased in all treatments in both greenhouse and field trials which is a good indication that these technosols can be reclaimed for agricultural use.

CHAPTER 1

INTRODUCTION

1.1 Background of the study

This study is prepared as part of a research funded by the Volkswagen Foundation entitled: Sustainable Restitution and Re-cultivation of Artisanal Tantalum Mining Wasteland in Central Africa “Coltan Environmental Management”. This is an on-going research project which an interdisciplinary research team is investigating at Gatumba Mining District (GMD) of Rwanda to establish a scientific baseline for the restitution and re-cultivation of soils affected by the previous coltan mining activities.

Coltan is the colloquial African name for columbite-tantalite, a metallic ore which produces the elements niobium and tantalum. Columbite minerals contain the element columbium (atomic number 41), which is another name for niobium (Nb). Tantalite is a mineral that contains tantalum (atomic number 73). Tantalum (Ta) is a metallic element that is grey coloured similar to steel, very dense (16 g cm^{-3}), ductile and malleable. It has a high melting point of $2996 \text{ }^\circ\text{C}$ and resists corrosion (Wickens, 2004).

Several unregulated, artisanal small to medium-scale mines have been run in Central African countries like Rwanda, Burundi, Congo, and Uganda, resulting from high tantalum and tin prices to severe poverty level of people, disorganized politics and the financing of civil wars. The remains of ceased mining activities are degraded, unproductive wasteland without any procedures of adequate land re-cultivation. Due to high population pressure and intensively farmed land, people cultivate agricultural crops on poor mine spoils and use them for pasture. The aim of the Coltan Environmental Management project is to study the environmental impact of open-cast coltan mines and to give recommendations for re-cultivation and restitution of mining wasteland (Paulmann, 2012).

This study was conducted on technosols from GMD. Technosols comprise a new reference soil group (RSG) and combine soils whose properties and pedogenesis are dominated by their technical origin. They contain a significant amount of artefacts (something in the soil recognizably made or extracted from the earth by humans), or are sealed by technique hard rock (material created by humans, having properties unlike natural rock). Technosols are often referred to as urban or mine soils. They are recognized in the new Russian soil classification system as “Technogenic Superficial Formations” (IUSS Working Group WRB, 2006). Some of the soil materials used in this study came from pegmatite rock where coltan was mined. Pegmatite is a very coarse-grained (usually larger than 2.5 cm in size), intrusive igneous rock composed of mainly quartz, feldspar and mica (Dewaele, 2007).

Other substrates used in the study were lixisol B_t horizon and cambisol since they predominate in Gatumba. Lixisols comprise soils that have a higher clay content in the subsoil than in the topsoil as a result of pedogenetic processes (especially clay migration) leading to an argic subsoil horizon. Lixisols have a high base saturation and low-activity clays at certain depths. Many Lixisols are included in: Argissolos (Brazil); sols ferralitiques faiblement desaturés appauvris (France); and Red and Yellow Earths, Latosols or Alfisols with low-activity clays (United States of America). Cambisols combine soils with at least an incipient subsurface soil formation. Transformation of parent material is evident from structure formation and mostly brownish discoloration, increasing clay percentage, and/or carbonate removal. Other soil classification systems refer to many Cambisols as: Braunerden (Germany), Sols bruns (France), Brown soils/Brown Forest soils (older US systems), or Burozems (Russian Federation). FAO coined the name Cambisols as adopted by Brazil (Cambissolos); US Soil Taxonomy classifies most of these soils as Inceptisols (IUSS Working Group WRB, 2006).

To improve the soil fertility, *Tithonia diversifolia*, commonly known as Mexican sunflower is used. *Tithonia diversifolia* is an annual, aggressive leafy weed growing to a height of 3.0 m or more and adaptable to most soils (Jama *et al.*, 2000; Olabode *et al.*, 2007). It has been used successfully to improve soil fertility and crop yields in Rwanda (Drechsel and Reck, 1998), Kenya (Jama *et al.*, 2000), Nigeria (Ayeni *et al.*, 1997), and Malawi and Zimbabwe (Ganunga *et al.*, 1998).

1.2 Statement of the problem

Coltan mining in the Gatumba Mining District (GMD) has commonly been practised in open casts and thus has left behind large areas with degraded land. Due to land shortage, technosols on mine spoils have become under increased use for agricultural production. Crops in GMD are commonly grown on Technosols composed of pegmatite materials (waste ground rock materials from coltan mining) which are poor in total and available nutrients and therefore low in soil fertility. Technosols are the major soils in the western province of Rwanda where coltan is mined.

To improve soil productivity in the GMD, local farmers have either covered pegmatite material with substrate from B horizons from the margins of casts or have prepared Technosols from pegmatite-subsoil mixtures. However, the productivity of such substrates has not been investigated. Moreover, there exists almost no knowledge about the effect of the application of deficient nutrients from inorganic and organic sources on crop yields in the GMD.

1.3 Research objectives

The broad objective of this study was to evaluate the suitability and the effect of using tithonia leaves and inorganic fertilizers in the rehabilitation of technosols of Gatumba mining district on soybean production and soil chemical property changes.

The specific objectives of this research were:

- 1) To evaluate the suitability of two Technosol substrates (pegmatite and pegmatite-Lixisol B_t mixture from the GMD) on soybean performance in the greenhouse.
- 2) To determine and compare the effects of incorporated tithonia leaves and different inorganic fertilizers to Technosol on soybean production and plant nutrients uptake (N, P, and K).
- 3) To determine the effects of the degraded soils of GMD on soybean performance in the field

1.4 Research hypothesis

The hypotheses of this research were:

1. Technosol materials have poor fertility status and do not present any advantages for plant growth
2. Inorganic fertilizers and tithonia biomass incorporated into soil have a positive effect on plant nutrient uptake (N, P and K)
3. Technosols of GMD become very poor in nutrients when left in the fields and cannot be reclaimed for agricultural use.

1.5 Justification of the study

The results of this study will not only be important for rehabilitation of mining areas in the Gatumba Mining District but also for similar areas in Rwanda (Gitarama and Mukura forest in the southern province), and in other African states. The field, greenhouse and lab work on the GMD soils in western Rwanda has provided information on the reclamation of GMD soils and similar soils in Central Africa. Small scale agriculture is almost the only

option for the population of Gatumba which means the restoration of these degraded land resource is highly important. Up to now there exists little knowledge about the capacity of technosols to produce crops. Furthermore, only few studies have investigated the effect of application of deficient nutrients from inorganic and organic sources on crop yields in the GMD and very little in the central African mined soils. Therefore, a study of this nature to investigate the productivity of technosols from coltan mining area will contribute to the better management of technosols and rehabilitation of mined areas.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Rwanda is not a globally significant producer and consumer of minerals. In 2009, however, Rwanda's share of the world's tantalum mine production amounted to about 9%, and tungsten, 1%. In the mining and quarrying sector accounted for about 1% of the gross domestic product. About 50,000 Rwandans were employed in the mining sector in 2007 (Banque Nationale du Rwanda, 2009). The workers' earnings and productivity are low, only team leaders earn enough to make a living from mining (Pourtier, 2004).

Rwanda's national boundaries encompass some of the tantalite deposits that also occur in the DRC and Burundi. Most production is carried out by artisanal miners for private companies like Gatumba Mining Concession (GMC) and some for the Rwanda Government under Rwanda Geology and Mines Authority (RGMA). Coltan mining and trading often harm the local population, wildlife and the environment (Wickens, 2004), for example through unregulated mining in natural reserves, land expropriation, land degradation, unfair social compensation and high potential for political conflicts (Reetsch, 2008). The previous coltan mining activities in GMD have also contributed to soil fertility decline and poor crop yields which have led to the necessity for reclamation of this land for agricultural purposes.

2.2 Coltan Mining

Minerals that contain tantalum (atomic number 73) are usually referred to as tantalite. Columbite minerals contain the element columbium (atomic number 41), which is another name for niobium. Coltan contains columbite and tantalite and is colloquially used as an abbreviation (Wickens, 2004). Tantalum is mainly used as a capacitor in electronics, e.g. mobile phones, laptops and digital cameras. Other industries and branches using tantalum are

medicine, abbreviation chemistry, aircraft and the car industry (Wickens, 2004). Columbium [niobium (Nb)] is vital as an alloying element in steels and in super alloys for aircraft turbine engines and is in greatest demand in industrialized countries. It is critical to the United States because of its defense-related uses in the aerospace, energy, and transportation industries (Cunningham, 2001).

Most of the coltan mines are open-cast mines, i.e., they are aboveground. Tantalum ores are found primarily in Australia, Canada, Brazil, and central Africa, with some additional quantities originating in south East Asia and China. The major Africa mining area is located at the western border of Rwanda, in the Democratic Republic of Congo, Uganda and Burundi. Due to political instabilities in central Africa, there has been a significant decline in mining investment activities since 2000 (Wickens, 2004).

From 1929 to 1985, the mining of coltan and tin ore in the GMD was conducted in a semi-industrial mode. The production was 18,000 tons of cassiterite and columbotantalite concentrate. As the mining leases are still valid, small scale artisanal tin and tantalum mining has been going on since 1985. The remains of quartzitic rock overburden, sand and amounts of mica are omnipresent in the area (Reetsch , 2008; Flügge *et al.*, 2007). The major coltan area in Rwanda is situated in the highlands west of Kigali the capital of Rwanda. Rwanda's coltan industry comprises small cooperatives and artisanal mining groups (Fetherston, 2004). Cunningham (2001) estimated the coltan production in 2001 in Rwanda at about 350 tons, containing 90 tons tantalum. Central Multi-Services SARL (CMS) alone produced around 180 metric tons per year (t/yr) of columbite-tantalite in 2009. Gatumba Mining Concessions Ltd GMC plans to spend \$2.5 million on building 10 new small processing plants by late 2014 (Holland, 2009b; Centrale Multi-Services SARL, 2010).

2.3 Agricultural productivity of Rwanda

Rwanda is chiefly characterized by low urbanization and high labour force engaged in traditional and subsistent agriculture (May, 1995). The country area is sectioned into 56 % arable land and permanent crops, 19 % forest area, 18 % pasture and meadows, and 7 % inland water. Major crops are bananas and plantains, common bean and soybean, sweet potato, cassava, coffee, groundnut, maize, millet, potato, pumpkin, rice, sorghum, sugar cane, tea, different fruits and vegetables, wheat, and yam (FAOSTAT, 2007). Primary exports are coffee and tea. Verdoot and van Ranst (2003) divided the country into 12 agricultural zones (Figure 1). Each agricultural zone is characterized by different environmental properties. The Gatumba Mining District is located in the agricultural zone 7 which is called the Central Plateau.

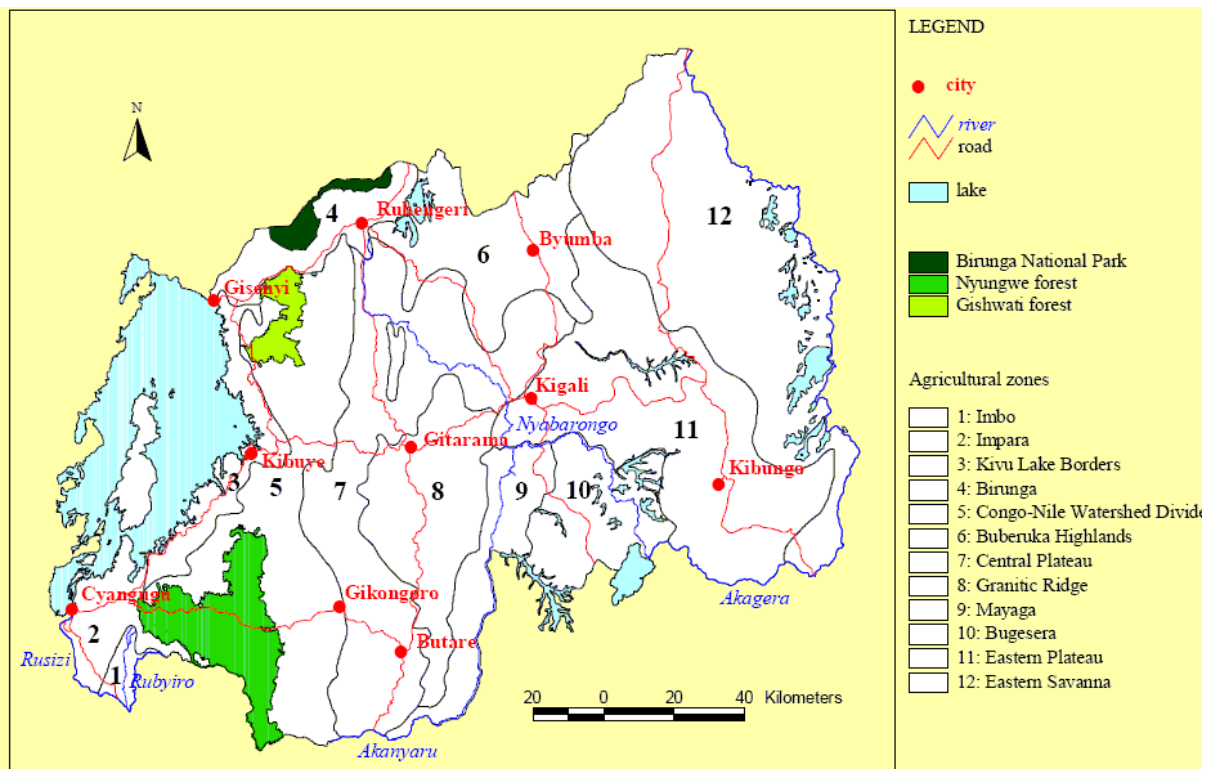


Figure 1: Agricultural zones and national parks of Rwanda (Verdoot and van Ranst, 2003)

The central plateau is at an average altitude of 1,700 m, the annual rainfall amounts to 1,200 mm and the average temperature attains 19 °C. If the humus-bearing horizons are conserved, the soils can be used for the cultivation of a whole range of climatically adapted crops (Verdoot and van Ranst, 2003). There are three agricultural seasons that are used for agriculture. Two correspond with the rainy seasons (Season A: September to December, Season B: Mid January to May). The third season (from June to September) allows a third harvest of crops cultivated in poorly drained valleys (Verdoot and van Ranst, 2003). The soils in the Central Plateau where Gatumba mining district is located are mainly cultivated with root crops like cassava or sweet potato but also some grain legumes like soybean and common beans.

Soils which are not affected by mining in the tropical highlands of Rwanda are cultivated with banana (*Musa L.*), cassava (*Manihot esculenta Crantz*), and sweet potato (*Ipomoea batatas L.*) as major crops and legumes like groundnut (*Arachis hypogaea*), soybean (*Glycine max L.*) and pea (*pisum sativum L.*).

2.4 Background of soybean production in Rwanda

Soybeans were introduced into Rwanda by INEAC [Institut National pour l'Étude Agronomique du Congo Belge] in the 1920s. Farmers started showing interest in soybeans in 1960. In 1969 production covered 550 ha and in 1973 there were 1,640 ha. The main reasons for such interest are: 1. Intensive extension work by the nutrition centres scattered around the country. These centres have demonstrated how to cultivate and how to prepare soybeans in the form of milk, cheese and flour. 2. Soybeans are more resistant to diseases than beans (*Phaseolus vulgaris*), which are a basic staple of Rwandans (Whigham 1975). Inoculated soybeans at the Rubana station (ISAR) gave yields of 1,800–2,000 kg/ha, and on peasant farms 1,400 kg/ha. Rwanda started commercial soybean production in 1961 with 230 tonnes,

peaked in 2006 with 27,128 tonnes. Production in 2007 was 25,000 tonnes (Shurtleff and Aoyagi, 2009).

Soybean was chosen as a test crop in this study since it is one of the representative crops for the Rwandan subsistence agriculture (Verdoot and van Ranst, 2003). It is locally grown by GMD farmers due to its relatively high oil and protein content in its seeds and high nutritional quality (Hoff *et al.*, 1982). Soybeans provide a nearly complete protein diet for poor people who cannot afford milk and meat in Rwanda. Soybean is a high N₂ fixing plant and an average of 50–60% of soybean N demand can be met by biological N₂ fixation (Salvagiotti, 2008).

2.5 Restitution and recultivation of coltan mining wasteland in Rwanda

Open-cast mining has disturbed large areas of land and has formed large landscapes in Gatumba mining district (GMD). These areas are either sparsely covered with less dense vegetation or the vegetation is absolutely missing. The extreme low content of soil organic matter (SOM) in reclaimed areas characterizes the soils of the GMD. The redistribution of material from former top soils of reclaimed sites is not practised.

Small-scale farming systems have been developed. The increase and storage of SOM in agro ecosystems that has been established on mine spoils is very limited due to low biomass densities (Reetsch, 2008).

Mine spoils are mostly cultivated with pioneer crops like cassava or sweet potato (Reetsch, 2008). The average farm size in the Gatumba mining district is 0.7 ha, where only small amounts of organic matter are returned to the soil as farmyard manure. The input of nitrogen in local crop rotations is partly increased by the cultivation of N₂-fixing legumes (Whitehead, 1995 and Cocking, 2003). Due to high cropping intensity, most of the soils are affected by

either erosion or deposition. Terracing has been sparsely realized in a few areas of the hilly country (Roose, 1996).

2.6 Role of legumes in biological nitrogen fixation

At present, the main nutrient limiting factors in sub-Saharan Africa soils are nitrogen and phosphorus (Van Straaten, 2002). Legumes are recommended to be a component of intercropped systems in tropical agriculture (Smithson and Giller, 2002). The legume-*Rhizobium* symbiosis results in dinitrogen (N₂) fixation that adds plant-available nitrogen to the soil system. Some of the fixed N₂ is recycled when legume crop residues decompose for the benefit of non-legume crops grown with or after grain legumes. Non-legume crops grown in rotation with legumes may also benefit from endophytic rhizobial (Newton *et al.*, 2011). Legumes form mycorrhizae which are called symbiotic fungus-root association (Hayman, 1986). Mycorrhizal connections between the intercropped components may provide a route of nitrogen transfer.

Nitrogen benefit to an intercropped cereal would be only achieved under low-yielding conditions like they exist in Rwanda. The rate of symbiotic N₂ fixation depends on the legume species and the site factors such as plant-available water, temperature, pH and soil mineral N content. Legumes differ in the amounts of N₂ fixation, for example groundnut (*Arachis hypogea*) and soybean (*Glycine max*) are considered to be high in N₂ fixation in tropical soils (Smithson and Giller, 2002).

Soybean (*Glycine max. L.*) is one of the most important nutritious crops in the world. It contains 18-22 % oil and 40-42 % protein (Mounts *et al.*, 1987). The nutrient content of the plant is important in understanding the response of the plant to different nutrient levels. Not only is the concentration of the nutrient supply important, but the ratios of the nutrients also modify the uptake pattern in most plants (Weigel, 1970). In soybean (*Glycine max. [L] Merr.*),

high yields are associated with greater N remobilization from vegetative tissues to the seed. Hence, this N mobilization will diminish leaf N content and thus, it will reduce leaf photosynthetic rate. Therefore, in a high-yielding environment, grain yield potential may be restricted by N supply (Thies *et al.*, 1995). However, yield response of soybean to fertilizer N has been inconsistent at economically acceptable levels (Barker and Sawyer, 2005; Gan *et al.*, 2003; Schmitt *et al.*, 2001).

Biological N₂ fixation (BNF) and mineral soil or N fertilizers are the main sources of meeting the N requirement of high-yielding soybeans. However, antagonism between nitrate concentration in the soil solution and the N₂ fixation process in the nodules is the main constraint the crop faces in terms of increasing N uptake (Streeter, 1988) when no other abiotic stress that reduce BNF activity occurs, e.g. soil pH (Parker and Harris, 1977), soil moisture or soil temperature (Purcell *et al.*, 2004). Maximum N₂ fixation occurs at reproductive stages (e.g bloom tags covering: R3 to beans filling half the space in the pod: R5) of soybean development (Zapata *et al.*, 1987), and any gaps between crop N demand and N supply by N₂ fixation must be met by N uptake from other sources.

The recommended fertilizer rates for soybean production in Gatumba (western province of Rwanda) are 100 kg diammonium phosphate (DAP: 18%N and 20%P) ha⁻¹ in addition to 10 tons ha⁻¹ of a good compost manure (MINAGRI, 2007).

2.7 Combining inorganic and organic nutrient sources (tithonia) for soil fertility replenishment

The beneficial effects of combined organic and inorganic nutrients on soil fertility have been repeatedly shown, yet there are no guidelines for their management (Hatfield, 1997; Bationo *et al.*, 1995). Organic materials influence nutrient availability (i) by nutrients added, (ii) through mineralization- immobilization patterns, (iii) as an energy source for

microbial activities, (iv) as precursors to soil organic matter (SOM), and (v) by reducing P sorption of the soil. Unfortunately, there is lack of crucial information on the nutrient content and quality of the organic inputs (Hatfield, 1997). The P content of plant residues and manure is normally insufficient to meet crop requirements hence the need for inorganic fertilizers to supply immediate available nutrients. However, it is through the formation of SOM that organic materials show longer term residual effects than do inorganic fertilizers. The use of inorganic fertilizers alone can even lead to a decline in SOM, while fertilizers combined with organics or organics used alone can maintain SOM levels (Bationo *et al.*, 1995).

Unused, non-traditional organic resources grow on or near smallholder farms in GMD. Some have relatively high nutrient concentrations, but little is known about their potential as nutrient sources to improve soil fertility and crop yields.

One such organic resource is the green biomass of *tithonia diversifolia* which is high in nutrients, averaging about 3.5% N, 0.37% P and 4.1% K on a dry matter basis (Jama *et al.*, 2000). Elsewhere, application of a high-quality organic material, tithonia [*Tithonia diversifolia* (Hemsley) A. Gray] leaves, combined with inorganic P in a pot trial resulted in greater maize biomass and P uptake than from equal amounts of nutrients added from inorganic fertilizers (Gachengo, 1996). In their study in western Kenya, Jama *et al.* (2000) revealed that crop yield can be much greater with combined use of tithonia and P fertilizer than with solely application of NP mineral fertilizer when tithonia overcomes an additional nutrient constraint such as K.

Field and farm experiments in Kenya have shown that the combination of locally available organic sources (*Tithonia diversifolia*) and inorganic locally available reactive phosphate rock resources can give similar results to the application of imported fertilizers e.g. urea and TSP (Buresh *et al.* 1997). The biomass of tithonia used for soil fertility improvement generally includes both green tender stems and leaves but not the woody stem. Biomass

production and nutrient concentrations of tithonia, however, are sometimes determined for only green leaves without the green stems, and much of the literature on tithonia does not clearly indicate whether green tender stems were included in reported measurements of biomass production and nutrient concentrations (Jama *et al*, 2000).

The stage of soils that has developed on a mine spoil of the Gatumba Mining District depends on the age of the mine spoils. In early stages, the soils often were extremely low in soil organic carbon (SOM). In older stages, the soils mostly exhibited higher SOM contents.

The slopes in the study area (GMD) vary between 5 and 55 %. High slopes cause soil erosion which result in decreasing SOM contents in top soils (Roose and Barthès, 2001). Soil fertility is closely linked to SOM whose status depends on input, e.g. biomass management, and output, e.g. mineralization, leaching and erosion (Roose and Barthès, 2001). SOM plays an important role in sustainable agriculture (Dang and Klinnert, 2001).

2.8 Phosphorus sorption by soils

Phosphorus is not chemically stable in the water-soluble form in the presence of soil. Water soluble P in soil solution readily reacts, largely with aluminium and iron, to form less soluble, more stable compounds. The reactions mostly take place on the surfaces of soil constituents such as clays; oxides of iron and aluminium; organic matter; and aluminium and iron compounds coating surfaces of sands. After the initial surface reaction, the adsorbed P diffuses slowly towards the interior of the particle and so becomes less available to plants. The whole reaction, adsorption plus penetration, is called sorption (Bolland *et al*; 2006). Penetration of adsorbed P into the soil particles continues even in dry soil, albeit more slowly. As a result of sorption of P by soil, the concentration of P in soil solution is usually very low, typically less than 0.2 µg P/mL (0.2 mg P/L). “Fixation” is sometimes used to describe sorption and sometimes to describe the penetration reaction (Bolland *et al.*, 2006).

Phosphorus deficiency is widely considered the main biophysical constraint to food production in large areas of farmland in sub-humid and semiarid Africa (Penning de Vries and Djiteye, 1982). Phosphorus dynamics in soils are complex, because they involve both chemical and biological processes and the long-term effects of sorption (fixation) and desorption (release) processes.

Phosphorus is either sorbed or desorbed by the soil to maintain a nearly constant P concentration in soil solution near the root hair. However, very close to the root hair, the active uptake of P will deplete P. This causes a concentration gradient towards the root hair and allows P to diffuse toward the root hair (Bolland *et al.*, 2006). A high P sorption capacity can promote more rapid dissolution of Phosphate Rock, but the low soil solution P concentration resulting from high P sorption may limit plant growth (Van Straaten, 2002). A subsequent field study showed that tithonia application reduced P sorption in the soil up to 16 weeks (Nziguheba *et al.*, 1998) and might account for the increased plant growth and uptake of P from the combined nutrient sources.

2.9 Matongo rock phosphate versus mijingu rock phosphate in replenishing soil P

One of the most sensible ways of replenishing soil fertility is the use of available natural resources, and phosphate rocks are one attractive alternative for replenishing phosphorus in soils that have been depleted of this nutrient. The success of phosphate rock applications in the main farming areas of East Africa has helped increased crop yields by large amounts (Van Straaten, 2002). Direct application of indigenous rock phosphates has been viewed as an attractive option for building soil P fertility because it potentially involves lower production costs and capital investments than production of water-soluble P fertilizers from indigenous rock phosphate sources (Hammond *et al.*, 1986; Rajan *et al.*, 1996). There are many phosphate rocks (PR) deposits and occurrences in Sub-Saharan Africa (Van Straaten,

2002). Igneous and residual phosphate accumulations have been found in Burundi. The residual igneous phosphate deposit at Matongo, 70 km north of Bujumbura (3° 4' S; 29° 37' E) was discovered in 1975 during an airborne geophysical survey (Songore, 1991). The residual phosphatic zone is up to 55 m thick.

The composition of the ore varies strongly. A typical sample from the weathered phosphate ore contains approximately 30% fluor-apatite and 17% caxonite (an iron-phosphate mineral); the rest is composed of clay, feldspar and limonite (Kurtanjek and Tandy 1989). The solubility of the Matongo apatite is low: the citric acid soluble P of the phosphate concentrate is 1.6% (IFDC, quoted in van den Berghe, 1996). Over the last few decades, the deposit was appraised by the United Nations, by the British Sulphur Corporation and various other agencies and institutions. The detailed feasibility study showed reserves of 17.3 million tonnes of ore at 11.0% P₂O₅ (cutoff 5% P₂O₅) or 40 million tonnes at 5.6% P₂O₅ (Kurtanjek and Tandy, 1989).

Minjingu rock phosphate fertilizer from northern Tanzania has a high phosphate content (12.8% total P, 3.03% neutral ammonium citrate soluble P) (Karanja *et al.*, 2004). It has been found to be a cheap source of phosphate fertilizer. A number of studies have highlighted the suitability of Minjingu PR as a P source for crops in P-deficient soils (Buresh *et al.*, 1997). For example, Bromfield *et al.* (1981) reported a relative agronomic effectiveness (RAE) of 75% for Minjingu PR in five seasons following application to maize in western Kenya. Relative agronomic effectiveness is defined as yield increase with PR relative to that with TSP expressed as a percentage.

2.10 Improving rock phosphate solubility

Naturally occurring phosphate rocks (PRs) differ widely in their mineralogy and chemistry. The chemical reactivity or solubility of phosphate rocks is a measure of the PR's

ability to release P for plant uptake. Reactivity is defined by Rajan *et al.* (1996) as “the combination of PR properties that determines the rate of dissolution of the PR in a given soil under given field conditions.” The reactivity of sedimentary phosphate rocks is relatively high compared to those of igneous and metamorphic origin (Van Straaten, 2002).

Various methods have been used to improve the solubility of rock phosphates. They include: partial acidulation with H_2SO_4 or H_3PO_4 (Hammond *et al.*, 1986; Mackay and Wewala, 1990), partial acidulation with elemental S through biological processes (Longanathan *et al.*, 1987). Other materials also found to be effective in enhancing P solubilisation when mixed with less reactive rock phosphates are organic acids and animal manures (Ikerra, 1994; Mahimairaja *et al.*, 1994). The products of decomposition of manures include simple and complex acids (Stevenson, 1994) which react with Ca in the apatite thus, allowing P to solubilise with ease. However, there is little information in the literature, on the use of green manures to enhance the solubility of rock phosphates (Karanja *et al.*, 2004).

Most beneficial results of phosphate dissolution through phospho-composting results have been achieved when using a sedimentary or biogenic phosphate rock as inorganic P-source (Lompo, 1993; Mathur *et al.*, 1986; Singh and Amberger, 1991; Tian and Kolawole 1999). Applying composts with less reactive mainly igneous PR sources showed no positive responses in P-deficient soils of eastern Uganda and this practice remains a challenge (Oshier, 2002).

CHAPTER 3

3.0 MATERIALS AND METHODS

3.1 Study area description

The study area of the Coltan Project where field trials were conducted and from where the substrates (pegmatite and Lixisol B_t material) for the greenhouse experiment were collected is the Gisuma catchment, a sub-area of the Gatumba Mining District (GMD) (Figure 2). The GMD is situated next to the Nyabarongo River between the longitudes 29°37' and 29°40' E and the latitudes 1°53' and 1°56'S. The “natural” soils (soils which have developed outside of the mining areas) of the GMD are representative for the tropical highlands of Rwanda. Typical Soil Reference Groups found in GMD include Lixisols, Nitisols, Cambisols, Gleysols and Umbrisols (IUSS Working Group WRB, 2006).

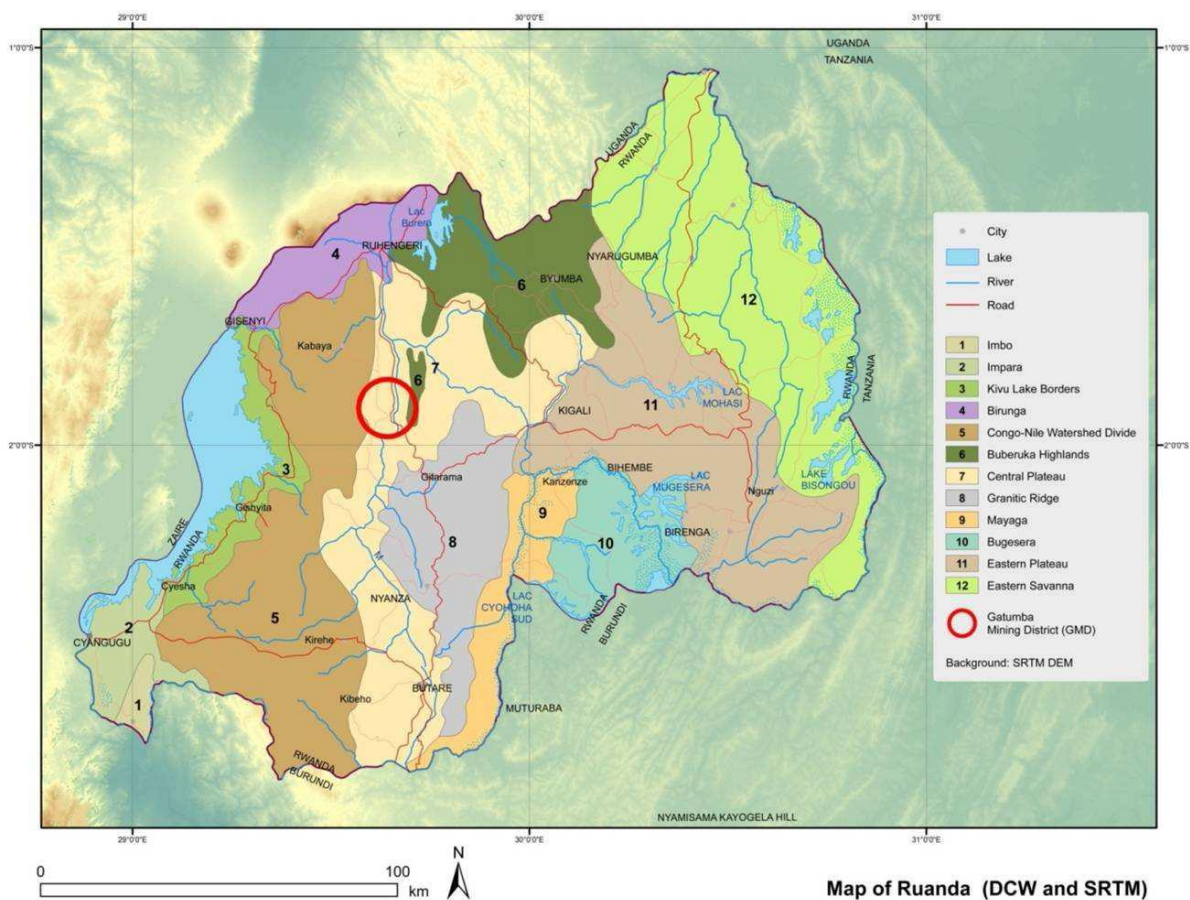


Figure 2: Location of the investigation area Gatumba Mining District (red circle), Rwanda (Paulmann, 2012)

The annual rainfall in Gatumba varies between 1,300 and 1,500 mm. This abundant rainfall has totally leached the soils that have developed from poor parent materials such as sandstone, quartzite, quartzophyllite and granite. The average annual temperature of the area is between 15 and 18°C mainly due to high altitude (2,100 m above sea level). The characteristics of rainfall during the study period are shown in Figure 3. The total rainfall received in 2011 short rain season was 820.9 mm. The rainfall peaks coincided with a rainfall pattern expected for Gatumba mining district of Rwanda during the month of November when this study was carried out.

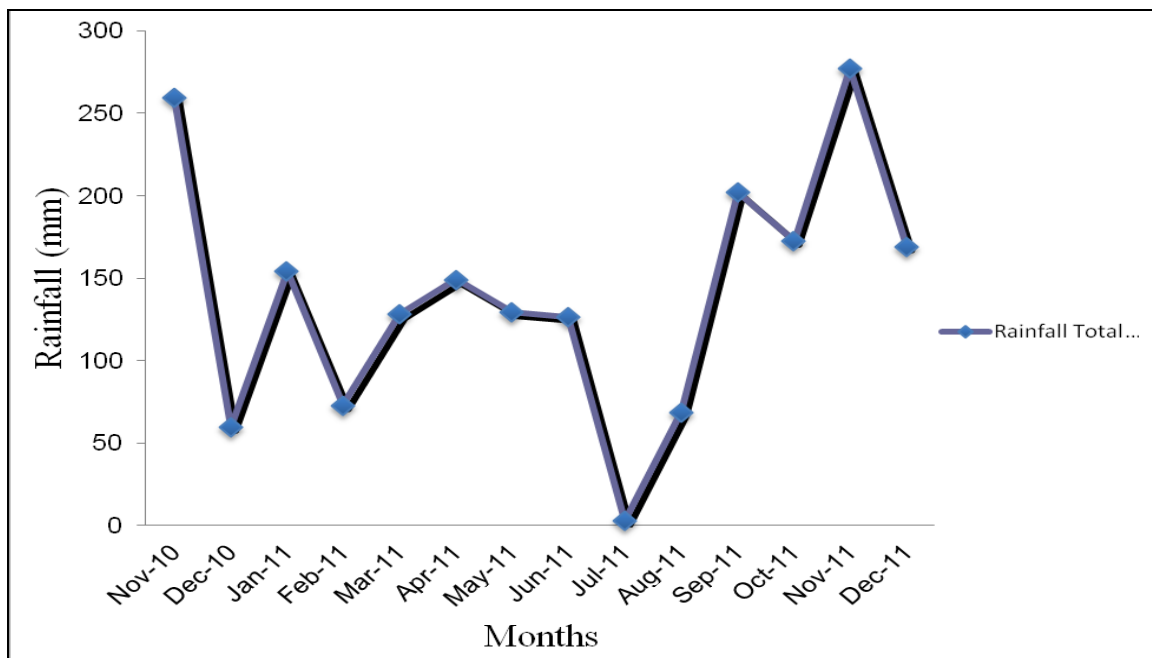


Figure 3: Rainfall amount during 2011 short rain (September to December 2011) at Gatumba Mining District, Rwanda (Measured with Davis weather station installed on the experimental site)

3.2 Establishment of greenhouse experiment

During the short rainy season in September 2011, the argic B horizon (B_t) from a Lixisol in the Gatumba mining district was sampled and used for the greenhouse experiment. Pegmatite waste material from mining activities which had been dumped next to excavated pits was also collected and used alone and mixed with lixisol B_t (1:1) in the greenhouse

experiment. This mixture was done to improve the texture of pegmatite which was initially sandy.

The substrates collected in the Gatumba mining district were transported to the Faculty of Agriculture at the National University of Rwanda (Butare) where they were air-dried and sieved with a 4 mm sieve. A total of 23 pots (diameter: 20 cm; height: 22 cm) were filled with 5 kg (air-dry basis) of pegmatite material each. A mixture (1:1) of Lixisol- B_t and pegmatite materials was prepared and 23 more pots were filled with 5kg of the pegmatite-soil mixture. Materials from the upper 10 cm of the pots (2 kg) were removed and mixed with mineral fertilizers according to the greenhouse experiment treatments given in Table 1. Tithonia biomass (5t dry matter ha⁻¹ of leaves) as recommended by Van Straaten, (2002) was incorporated before filling the pots again with top soil substrates.

A completely randomized design was used for the 5 treatments (Table 1), each was replicated 4 times, giving 20 pots for the pegmatite and another 20 pots for the pegmatite-Lixisol B_t mixture, thus adding up to 40 pots. Besides, 6 additional pots were included, that is 3 filled with pegmatite substrate alone and 3 filled with the mixture (pegmatite and Lixisol B_t) which were used to assess watering needs. In total, 46 pots were used for the Greenhouse experiment.

Table 1: The greenhouse experimental treatments for organic and mineral inputs

Treatments	Type of fertilizer input	Rate of input respectively
1	Tithonia (Control)	5t DM ha ⁻¹
2	Tithonia+TSP	5t DM ha ⁻¹ +50 kg P ha ⁻¹
3	Tithonia+MtRP+TSP	5t DM ha ⁻¹ +50 kg P ha ⁻¹ (70%MRP, 30% TSP)
4	Tithonia+MtRP+AS	5t DM ha ⁻¹ +50 kg P ha ⁻¹ +50 kg N ha ⁻¹
5	Tithonia+MtRP	5t DM ha ⁻¹ +50 kg P ha ⁻¹

MtRP=Matongo Rock Phosphate, AS=Ammonium Sulphate, DM =Dry Matter, TSP=Triple Superphosphate

Note that for the greenhouse experiment, there was no true control reported since the materials used were very poor and could not grow any crop. The moisture content of the pegmatite and the mixture substrate was maintained at field capacity (60% of the soil water holding capacity) for 1 week before planting and during the growing period in the greenhouse. The seeding density for soybean was 3 seeds per pot.

3.3 Establishment of field experiment

During the short rain season of September to December 2011, field trials for soybean were carried out on pegmatite heaps, Lixisol-pegmatite mixture and on a cambisol in the Gatumba mining district. Five treatments plus a control (Table 2) on the mined soils were used under local farmer management. The experiment was laid in a randomized complete block design with 3 replications per treatment. Blocking was done according to the slope of the landscape. Liming was done only on the mixture of pegmatite and Lixisol materials to reduce the soil acidity and to neutralize the aluminium toxicity. Lime was applied at the rate of 5 tons ha⁻¹ as recommended by Rwanda Agriculture Board, using broadcasting method.

Another similar experiment with same six treatments was conducted in farmers' field on a cambisol outside the quarry to compare the soybean yields between soils affected by mining (technosols) and none affected ones (Cambisol). Cambisol soil was chosen because of its abundance and its high use for agricultural activities in Gatumba mining district. It was not limed since farmers' practice was followed and farmers' in Gatumba grow soybean without lime.

Each plot measured 5.0 m x 4.5 m in size and soybean (variety PK6) was planted at a density of 43 plants per m². The sowing date was September 15th in 2011. The fields were rain-fed and weeds were manually controlled.

Table 2: The field experimental treatments for organic and mineral inputs

Treatments	Type of fertilizer input	Rate of input respectively
1	Tithonia	5t DM ha ⁻¹
2	Tithonia+TSP	5t DM ha ⁻¹ +50 kg P ha ⁻¹
3	Tithonia+MRP+TSP	5t DM ha ⁻¹ +50 kg P ha ⁻¹ (70%MRP, 30% TSP)
4	Tithonia+MRP+AS	5t DM ha ⁻¹ +50 kg P ha ⁻¹ +50 kg N ha ⁻¹
5	Tithonia+MRP	5t DM ha ⁻¹ +50 kg P ha ⁻¹
6	Control	0

MRP: Minjingu rock phosphate, AS: Ammonium sulphate, TSP: Triple superphosphate

For the field trial, the experimental layout is presented on the Appendix 3.

3.4 Soil sampling

Initial soil sampling was done on 10th August 2011 before the field experiment was established and the last sampling was carried out on 10th January, 2012 at the end of the

experiment. Soils which were used in the greenhouse were analyzed first in January 2012 before the start of experiment and in April 2012 at the end of the experiment.

For the field trial, preliminary and final soil sampling was done with an Eldelman auger at 0-20 cm for soil chemical analyzes which included total N, P, K, available P, exchangeable K and pH. Five cores of soil samples were taken in each plot and then bulked to one composite sample which was used for analysis.

For the greenhouse experiment, soils were initially evenly homogenized before the experiment and a representative sample was taken for analysis while at the end of the experiment, soils from each pot were thoroughly homogenized separately and then sampled for analysis.

3.5. Sampling and measurement of organic materials

Tithonia leaves that were used as green manure for this study were collected near the greenhouse at the National University of Rwanda and in Gatumba minding district then taken to Germany (Technical University of Braunschweig) for nutrient analyses, i.e., total N, P, K, Ca and Mg. The results for this chemical analysis of tithonia and the various fertilizer inputs are presented in Table 3 below.

Table 3: Chemical properties of *Tithonia diversifolia* leaves (T), matongo rock phosphate (MtRP), minjingu rock phosphate (MRP), triple super phosphate (TSP) and ammonium sulphate (AS)

Fertilizer type	Chemical properties (Total concentrations in %)						
	C	N	P	K	S	Ca	Mg
Tithonia	40.00	5.25	0.30	3.22	-	2.00	0.30
Minjingu RP	-	-	13.00	-	-	26.90	-
Matongo RP	0.19	0.01	4.80	-	-	-	-
TSP*	-	-	20.20	-	-	-	-
Ammonium Sulphate*	-	21.00	-	-	24.00	-	-

- : Not mentioned

*Source: Fertilizer supplier (YARA MILLA JAVA)

Soybean grain, shoots and roots were collected from each pot at the end of maturity phase and analyzed for total N, P and K. For the field trial, soybean grain, shoot and roots of 10 plants randomly selected from each plot were sampled. The soybean grains from the 10 plants in the same plot were pooled together and analysis for total N, P, and K at the Laboratories of National University of Rwanda. The same sampling and laboratory analysis procedures were done similarly for soybean shoot and roots.

3.5.1 Soybean plant height and number of pods

Soybean heights and number of pods per plant were measured at physiological maturity stage (17 weeks from planting) on 15th December 2011. This is the stage when, full yield potential had been realized. The same measurements were also taken at 17 weeks after planting in the greenhouse experiment that was carried out from 10th January 2012 to April 2012.

3.5.2 Soybean harvest

In the field trial, soybeans (grains, shoots and roots) were harvested at maturity from each plot but leaving out one row on each side of the plot to minimize the edge effect. Active nodules of five plants in each plot were counted. For the greenhouse experiment, all the three soybeans plants per pot were harvested at maturity and active nodules were counted. Note that nodules weights were included in the reported root weights. Threshing was done manually in clean containers to avoid loss of grains. Soybean shoots including empty pods were immediately measured for fresh weight while roots were thoroughly washed to remove the soils and left in a cool room for one day to be air dried before taking their weights using a precision balance (EJ6100 concrete density scale). A sample of 200 g of soybean shoots and roots was dried separately in the oven at 70°C to constant weight and used to calculate the shoot and root dry matter. The soybean grains in each plot were then air dried to 14% moisture content. This grain moisture content was monitored using a grain moisture meter on a representative sample. After harvesting, representative samples from each plot were taken to the laboratory for the analyses of total N, P and K. The same procedures were used for the soybean grown in the greenhouse where a representative sample from each pot was taken to the laboratory for analysis.

3. 6 Laboratory analysis

3.6.1 Soil analyses

Soil samples were analyzed for total N, P, K, cation exchange capacity (CEC) available P, exchangeable K, organic carbon, soil particle size (sand, silt and clay) and pH using the laboratory methods of soil and plant analysis as described by Okalebo *et al.*, (2002).

3.6.1.1 Soil pH

A total of 20 g (two replicates of 10 g each) of dried and pestled material of each soil sample (P10-13) were weighed in a 60 milli-liter (ml) bottle then 25mL distilled water (for pH water) was added with a dispenser. The mixture was stirred for 10 minutes, allowed to stand for 30 minutes (min) and stirred again for 2 min. The pH_{H_2O} (active acidity) value was then measured using a glass electrode PT 100 for 30 to 60 seconds until the values remained constant (Okalebo *et al.*, 2002). The electrode was then removed from the bottle, rinsed with distilled water before introducing it to the next sample. Similar procedures were again used but this time using KCl 1 M as extractant to determine the pH KCl which is a measure of potential or reserve acidity in soil.

3.6.1.2 Total nitrogen

Air-dried soil material was sieved through < 2 mm sieve and ground into fine powder and then sieved <0.25mm (60 mesh). A sample of 0.3 g of this soil was weighed into a labelled, dry and clean digestion tube and 2.5 ml of a digestion mixture (salicylic acid dissolved in sulphuric acid-selenium mixture) was added to each tube and the reagent blanks for each batch of samples. They were then digested at 110°C for 1 hour, left to cool and added three successive 1ml portions of hydrogen peroxide before raising the temperature to 330°C. When the solution turned colourless and the remaining sand white, it was allowed to cool and 25 ml distilled water was added to it and mixed until no more sediment dissolved.

Total N was then determined in the digests through distillation whereby free ammonia was liberated from solution by steam distillation in the presence of excess alkali (NaOH). The distillate was collected in a conical flask containing excess boric acid with drops of mixed indicator. Titration of the distillate was then carried out using N/140 HCl until colour changed from green to pink. The total ml of N/140 HCl used were recorded and used to

determine total N using the formula in Appendix 2. The total P and K determination of 5.0 ml sample for each was carried out by colorimetric without pH adjustment using ascorbic acid in a colorimetric measurement and total N was calculated as recommended by Okalebo *et al.*, (2002).

3.6.1.3 Available phosphorus

Two grams of soil were weighed into a 50 mL Erlenmeyer flask, tapping the scoop on the flask to remove all of the soil from the scoop. Twenty mL of extracting solution (reagent-grade ammonium fluoride (NH₄F) mixed with distilled water and 250 mL of previously standardized 1M HCl were added to each flask and shaken at 200 rpm or more for 5 minutes at a room temperature (24 to 27° C). Extracts were filtered using Whatman No. 42 filter paper. Phosphorus was then analyzed by colorimetry using a blank and standards prepared in the Bray P-1 extracting solution (Bray and Kurtz, 1945).

3.6.1.4 Exchangeable K, Ca, Mg, Na and cation exchange capacity

Five grams of air dried soil (<2 mm) were weighted into a clean plastic bottle with a stopper and 100 ml of 1 M (NH₄OAc) ammonium acetate solution (pH 7) were added. An internal standard and a repeat sample within each batch of test soils were included. The contents were shaken for 30 minutes and filtered through No. 42 Whatman paper. This soil extract was then used for K, Ca, Mg and Na determinations using atomic absorption spectrophotometer (Okalebo *et al.*, 2002). The concentration measurement was calculated using the formula: $\text{Mg kg}^{-1} \text{ K, Ca, Na and Mg in soil} = ((a-b) \times v \times f \times 1000) \div (1000 \times w)$
Where a = concentration of K, Na, Ca, and Mg in the sample extract; b = concentration of the element in the blank extract; v = volume of the extract solution; w = weight of the soil sample; f = dilution factor.

3.6.1.5 Organic carbon

Organic carbon in soils was determined by the sulphuric acid and aqueous potassium dichromate ($K_2Cr_2O_7$) mixture. A sample of 0.30 g of ground soil (<0.5mm) was weighted out into a clean labelled 100 ml digestion tube and added 2ml of distilled water. Ten ml 5% of Potassium dichromate solution was added and it was allowed to completely wet the soil and standards were prepared (Sucrose Carbon stock 50mg/ml used to make 20, 15, 10, 5 and 0 mg C standards). Slowly and carefully, 5 ml H_2SO_4 from a slow burette were added and the mixture was gently swirled to mix. It was then digested at 150°C for 30 min and allowed to cool after which 50 ml of 0.4% barium chloride was added. It was swirled to mix thoroughly, then brought to 100 ml mark by distilled water and allowed to settle overnight so as to leave a clear supernatant solution. An aliquot of the supernatant solution was transferred into a cuvette, and measurement of absorbance of the standards, the sample and the blank at 600 nm was performed. The content of total organic carbon in air dry soil expressed in %C was then calculated by the pilot program as described by Okalebo *et al.*, (2002).

3.6.1.6 Cation Exchange Capacity (CEC)

For cation exchange capacity, a sample of 25.0 g of soil was weighed into a 500 mL Erlenmeyer flask and 125 mL of the 1 M NH_4OAc added to it, then shaken thoroughly, and allowed to stand for 16 hours (or overnight). A 5.5 cm buchner funnel with retentive filter paper was fitted, the paper was moistened, applied light suction, and the soil was transferred. The soil was gently washed four times with 25 mL of NH_4OAc , allowing each addition to filter through but not allowing the soil to crack or dry.

The soil was washed with eight separate additions of 95% ethanol to remove excess saturating solution and each addition was allowed to filter through before adding more. The adsorbed NH_4 was extracted by leaching the soil with eight separate 25 mL additions of 1 M KCl, leaching slowly and completely as above. Soil was discarded and the leachate

transferred to a 250 mL volumetric flask. The concentration of NH₄-N in the KCl extract was then determined by distillation. Also NH₄-N in the original KCl extracting solution (blank) was determined to adjust for possible NH₄-N contamination in this reagent (Chapman, 1965). The CEC in Cmol_c was then obtained using the following calculations: CEC (meq/100g) = NH₄-N+ (mg/L as N) ÷ 14+ (NH₄-N in extract - NH₄-N in blank)

3.6.1.7 Soil particle size analysis

A sample of 50 g of air dry <2 mm soil was weighed out into a 400 ml beaker and was saturated with distilled water before adding 10 ml of 10% calgon solution. The suspension was transferred to the dispersing cup and about 300 ml of tap water added to it. The suspension was mixed for two minutes with an electric high speed stirrer then transferred into a graduated cylinder. The cylinder was covered with a tight-fitting rubber band and the suspension was mixed by inverting the cylinder carefully ten times. The time was noted and 2-3 drops of amyl alcohol were quickly added in order to remove froth and after 20 seconds the hydrometer was gently placed into the column. The hydrometer readings and thermometer measurements at 40 seconds were recorded. The cylinder was covered again with a tight-fitting rubber band and the suspension was mixed by inverting the cylinder ten times and then allowed to stand undisturbed for 2 hours after which both hydrometer and temperature readings were taken. The % sand, silt and clay were then calculated as described by Okalebo *et al.*, (2002).

3.6.2 Plant tissue analyses for N, P and K

A sample of 0.3 g of oven dried (70°C) and grounded plant tissue (<0.25mm, 60 mesh) was weighed into a dry clean tube and 2.5 mL of a mixture (Salicylic acid dissolved in sulphuric acid-selenium mixture) was added to each tube and the reagent blanks for each batch of samples. It was then digested at 110°C for 1 hour, removed to cool and three

successive 1 ml portions of hydrogen peroxide were added before raising the temperature to 330°C. When the solution turned colourless and remaining sand white, it was allowed to cool and then 25 ml distilled water was added and mixed until no more sediment dissolved.

Total N was then determined in the digests through distillation whereby free ammonia was liberated from the solution by steam distillation in the presence of excess alkali (NaOH). Further procedures are as described in section 3.6.1.2 above.

Phosphorus in plant tissues was analyzed by colorimetry. After digestion, the phosphate in the plant tissue sample reacted with the acidified ammonium molybdate to form an ammonium molybdophosphate complex. A blue coloured solution was generated from the reduction of the ammonium molybdophosphate complex by ascorbic acid. Since the intensity of the blue colour is proportional to the amount of molybdophosphorus present, the amount of light absorbed by the solution at 660 nm was measured and correlated with total P using a spectrophotometer as described by Watanabe *et al.* (1965).

Potassium in plant tissues was analyzed using atomic absorption method as described by Isaac *et al.* (1971). After digestion a solution containing the element in question was atomized and introduced into the acetylene/air mixture. The light source was provided by a hollow cathode lamp in which K acted as the cathode. This light was directed into the flame where it was absorbed proportional to the concentration of the element in the flame. Absorption was calculated based upon the measured difference in light intensity passing around the flame and that passing through the flame.

3.7 Secondary data collection

Secondary data was collected from the relevant sources, which included reports and unpublished data from projects undertaken in the areas regarding coltan mining activities and reclamation of waste mine spoils for agriculture use (e.g. RGMA report, 2011),

and review of past literature on soybean nutrient uptake and the use of integrated soil fertility management practices (ISFM).

3.8 Statistical analysis

The data collected from greenhouse and field trials were entered in Microsoft Excel and analysed using GenStat (4th edition) software. These data were analyzed statistically using two way analysis of variance (ANOVA) in a completely randomized design (for greenhouse experiment) and in a randomized complete block design (for field experiment). Means were separated using Duncan's multiple range tests and F-protected least significant difference (F-protected LSD) at 5% level of significance (VSN International, 2008)

CHAPTER 4

RESULTS AND DISCUSSION

4.0 An overview of the results presentation and discussion

The results of this study have been presented as follow: 4.1 deals with soil properties both at initial and end of Greenhouse and field experiments ,4.2 presents results of soybean performance as affected by various treatments in the field and Greenhouse experiments, and 4.3 presents results of Nutrients uptake by soybean as affected by experimental treatments.

4.1 Soil properties and as affected by various treatments

4.1.1 Soil properties in the greenhouse experiment

The initial soil chemical and physical properties of the Greenhouse experiment are shown in Table 4. The pH_{H_2O} for the two soils used in Greenhouse experiment (pegmatite and Mixture of pegmatite and lixisol) was acidic (6.3 and 5.8,respectively),while in the case of potential pH (KCl),the Mixture exhibited extremely low pH value (3.9) as compared to Pegmatite (5.1). In general, the contents of organic carbon, total N, available P and exchangeable K in all the three soil substrates were extremely low whereas that of total P and total K were extremely high, a reflection of high acidity of the soils and probably of the clay type that could fix K. The soil texture of the pegmatite substrate was loamy sand while that of the mixture was sandy clay.

Table 4: Soil chemical and physical properties at the beginning of the Greenhouse experiment (January 2012)

Property	Pegmatite	Mixture (1:1)
pH H ₂ O	6.3	5.8
pH KCl	5.1	3.9
Organic carbon (%)	0.0001	0.1
Total N (%)	0.0001	0.034
Available P (ppm)	0.01	0.51
Total P (ppm)	240.2	225.3
Exchangeable K(Cmol _c /Kg)	0.07	0.12
Exchangeable Na(Cmol _c /Kg)	0.40	0.45
Exchangeable Ca(Cmol _c /Kg)	1.10	1.60
Exchangeable Mg (Cmol _c /Kg)	0.45	0.62
Total K (ppm)	492.3	640.5
CEC (Cmol _c /Kg)	4.3	11.65
Sand (%)	87.5	51.5
Silt (%)	4.4	5.3
Clay (%)	8.1	43.2
Texture class	Loamy Sand	Sandy clay

CEC: cation exchange capacity

The soil chemical properties of substrates determined after soybean harvest in the Greenhouse are presented in Table 5. Pegmatite was significantly ($p < 0.001$) higher than the mixture in pH water, pH_{KCl} and available P. The mixture was significantly ($p < 0.05$) higher than pegmatite in exchangeable Mg and in total N especially in treatments that received ammonium sulphate fertilizer. The available P was higher in the pegmatite substrate that received Tithonia + Matongo Rock Phosphate + Ammonium Sulphate and was also higher in the mixture that received Tithonia and TSP. There was no significant ($p < 0.05$) difference between fertilizer treatments in pH, C, Ca, K, Na and Mg. No significant ($p < 0.05$) difference was observed between mixture and pegmatite soil in C, Ca, and K.

Table 5: Effect of tithonia green biomass and mineral fertilizers on soil properties at the end of the greenhouse experiment (April 2012) at the National University of Rwanda

Treatments	Exchangeable base cations (Cmol kg ⁻¹ soil)								
	pH _w	pH _{KCl}	%C	%N	Av.P ppm	K	Ca	Mg	Na
PEGMATITE									
T	7.3a	7.0a	0.05b	0.015f	1.45c	0.40b	1.54a	0.50de	0.40a
T+ MRP	7.2a	6.6ab	0.06b	0.013f	1.98bc	0.28b	1.49a	0.50de	0.43 a
T+ TSP	7.0a	6.3b	0.03b	0.016f	2.19ab	0.42b	1.06a	0.4e	0.40 a
T+MtRP +AS	6.7a	6.4ab	0.25a	0.034de	2.76a	0.37b	1.60a	0.53cde	0.40 a
T+MtRP+TSP	7.0a	6.7ab	0.18b	0.024ef	2.60a	0.52b	1.46a	0.46e	0.44 a
MIXTURE									
T	4.9b	4.2c	0.14b	0.025ef	0.22d	0.60b	1.62a	0.77bcd	0.48 a
T+MtRP	4.9b	4.1c	0.07b	0.055d	0.45d	0.60b	1.31a	1.00a	0.55 a
T+TSP	4.8b	4.3c	0.10b	0.048cd	0.68d	0.56b	1.95a	0.80bc	0.44 a
T+MtRP+AS	4.9b	4.2c	0.04b	0.404a	0.41d	0.64a	1.69a	0.86a	0.54 a
T+MtRP+TSP	4.9b	4.1c	0.22b	0.287b	0.41d	0.25b	0.89a	0.54bcd	0.45 a

T: Tithonia, MRP: Matongo rock phosphate, AS: Ammonium sulphate, TSP: Triple superphosphate. Means with different letter in each single column are significantly different between treatments and soil types at ($P < 0.05$) Duncan's multiple range tests.

Table 6 shows the changes of soil properties after the use of tithonia and mineral fertilizers. On pegmatite, all treatments showed a slight increase in total N and carbon though not significant ($p=0.05$). However, a significant increase in available P and pH at the end of the experiment was observed on pegmatite. Whereas, the mixture, had a significant increase only in pH but a significant decrease in available P. A slight increase in carbon and exchangeable K was observed on the mixture although not significant ($p=0.05$).

Table 6: Changes in soil chemical properties after the greenhouse experiment at the National University of Rwanda

Treatment	K(cmol_c/kg)	Av.P(ppm)	N_t (%)	pH	C (%)
Pegmatite					
T	0.24	1.44	0.015	1.85	0.051
T+TSP	0.33	1.97	0.015	1.15	0.025
T+MtRP+TSP	0.375	2.59	0.023	1.6	0.18
T+MtRP+AS	0.24	2.745	0.034	1.3	0.145
T+MtRP	0.295	2.175	0.013	1.49	0.06
Mixture					
T	0.305	-0.295	-0.009	0.335	0.035
T+TSP	0.32	0.165	0.014	0.4	0.05
T+MtRP+TSP	0.105	-0.1	0.253	0.23	0.12
T+MtRP+AS	1.215	-0.105	0.81	0.28	0.02
T+MtRP	0.35	-0.065	0.021	0.23	0.04
p value	0.220	<0.001	0.073	<0.001	0.106
SED	0.3378	0.4	0.1	0.4	0.1

T: Tithonia, MtRP: Matongo rock phosphate, AS: Ammonium sulphate, TSP: Triple superphosphate

P availability in relation to pH in soil substrates

A correlation study was done to establish whether P availability in soil depended on pH (Fig.4). It was found that the correlation was high and positive ($R^2=0.781$) which means that the availability of P in these soils was highly influenced by soil pH.

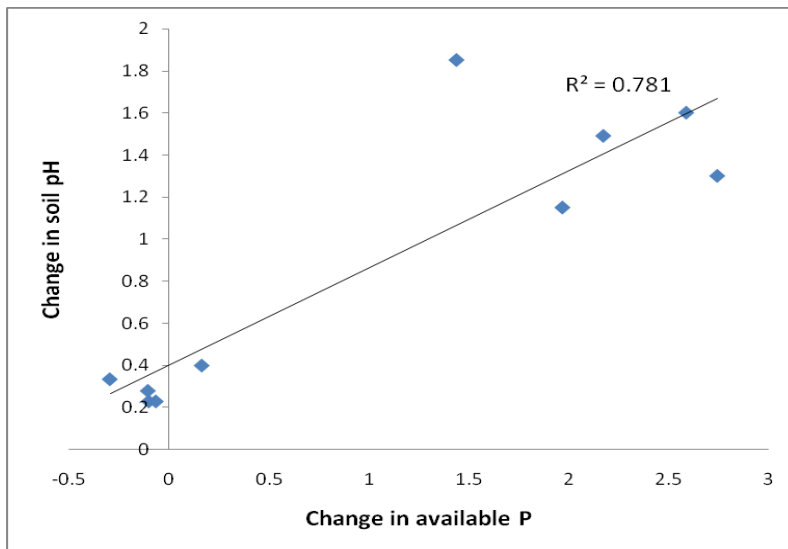


Figure 4. Relationship between pH changes and P availability in pegmatite and mixture substrates

In general, the results of this study are in agreement with those of Shokalu *et al.* (2010) who noted a significant progressive increase of soil pH at different rates of tithonia biomass application. This could have resulted from the release of base cations by the decomposition of tithonia leaves applied as green manure. The above results are also in agreement with the findings of Jama *et al.* (2000) and Shokalu *et al.* (2010) who reported a general increase in organic carbon, N, P and K, after application of various green manures over time. The significant increase of N, P and K on pegmatite than on the mixture was due to the poor initial status of the pegmatite substrate used and to the high N fixation by soybean which was enhanced by good abiotic environment e.g. soil moisture (Purcell *et al.*, 2004), soil pH (Parker and Harris, 1977) or soil temperature, (Soares Novo *et al.*, 1999). The higher N on pegmatite is also confirmed by the higher number of active nodules than the mixture. The total N decline in the treatment that received tithonia alone (5t DM ha⁻¹) shows that the overall N supply did not meet the soybean requirements and the crop had to remobilize the indigenous soil N (Salvagiotti, 2008).

The significantly (<0.01) higher increase of available P observed in pegmatite compared to the mixture may also be explained by the high pH, low organic matter, and low

clay and amorphous Fe content of the pegmatite which otherwise could have fixed P. There was a positive correlation between changes in pH and changes in P availability (Figure 4). Naidu *et al.* (1990) explained the increase in P-fixation with decreasing pH through interactions between added P and the soil matrix. They also found a positive correlation between the P-fixation rate and the contents of clay, organic matter and amorphous Fe.

4.1.2 Soil properties in the field experiment

Table 7 shows the initial chemical and physical soil properties of the field experiment (September - December 2011) at GMD. Results show that pegmatite had higher pH water (5.9) than the mixture (5.10) and cambisol (5.20) but had lower organic carbon, total N, available P and exchangeable K than the mixture and cambisol. In general, however, the values of organic C, total N, available P and K in the three soils were extremely low while total K and P values were extremely high just like those found in the Greenhouse substrates (Table 4). The pegmatite was sandy while the mixture was clay and the cambisol sandy clay. The CEC of pegmatite was lower ($5 \text{ cmol}_c \text{ Kg}^{-1}$) than the mixture ($11.64 \text{ cmol}_c \text{ Kg}^{-1}$) and the cambisol ($7.9 \text{ cmol}_c \text{ Kg}^{-1}$).

Table 7: Soil chemical and physical properties at the beginning of the field experiment (September 2011) at Gatumba Mining District

Property	Value		
	Pegmatite	Mixture (1:1)	Cambisol
pH H ₂ O	5.90	5.10	5.20
pH KCl	5.00	4.20	4.40
Organic carbon (%)	0.05	0.71	0.78
Total N (%)	0.01	0.11	0.09
Available P (ppm)	3.10	0.70	1.32
Total P (ppm)	253.20	215.30	238.90
Exchangeable K (Cmol _c /Kg)	0.07	0.12	0.17
Total K (ppm)	490.50	640.50	2475.20
CEC (Cmol _c /Kg)	5.60	11.64	7.90
Sand (%)	80.30	39.90	50.90
Silt (%)	11.70	22.50	18.40
Clay (%)	8.00	37.60	30.70
Texture class	Sandy	Clay	Sandy Clay

CEC: cation exchange capacity, Mixture (pegmatite plus Lixisol B_t (1:1))

The effects of tithonia and inorganic fertilizers application on soil properties for Field experiment are shown in Tables 8 and 9. Table 8 shows the effect of treatments on soil properties of each soil type in relation to the control while Table 9 shows the actual changes of chemical soil properties due to the treatments in relation to initial status of soil properties. For the field trial, the limed mixture had higher pH and organic carbon than pegmatite and cambisol. The limed mixture also had higher total N than pegmatite but not more than the cambisol. The mixture had also more exchangeable K than the pegmatite and the cambisol while the cambisol was higher in total K than the other two substrates. The mixture had a significantly ($p < 0.05$) higher total P but lower available P than the other substrates.

The higher total N content in the mixture than that of pegmatite might be partly explained by ammonium fixation in 2:1 clay minerals, as well as the formation of organo-mineral complexes on clay mineral and fine silt surfaces (Nieder *et al.*, 2010).

Table 8: Effect of tithonia green biomass and mineral fertilizers on soil properties at the end of the field experiment at Gatumba Mining District

Treatment	pH _w	pH KCl	C (%))	N (%)	Av. P(mg/kg)	Tot. P(mg/kg)	Exch.K (Cmol _c /kg)	Tot K(mg/kg)
Mixture + Lime								
Control	6.5ab	5.5ab	1e	0.084abc	2.12h	437.61bcde	0.21de	1121.97ab
T	6.2d	5.4bc	1.4c	0.098abc	2.39gh	381.51fgh	0.36b	995.76ab
T+MPR	6.3bcd	5.7a	1.2cd	0.116abc	5.21de	459.04bcd	0.34b	1027.04ab
T+TSP	6.2cd	5.1cd	1.7b	0.058abc	6.25cd	556.35a	0.47a	999.74ab
T+MPR+AS	6.3abcd	5.3bcd	1.9a	0.18a	7.47c	535.86a	0.31bc	1367.55b
T+MPR+TSP	6.0e	5.1cde	1.3cd	0.0015c	4.02efgh	446.79bcd	0.34b	1284.49ab
Pegmatite								
Control	5.8efg	5.1de	0.4g	0.0075c	3.14fgh	304.02j	0.09f	594.74a
T	6.5a	5.1cde	0.4g	0.011c	9.61b	337.77hij	0.21de	792.63ab
T+MPR	6.4abc	5.4b	0.4g	0.014c	10.23ab	385.1fgh	0.23de	742.07ab
T+TSP	6.3bcd	4.9ef	0.5fg	0.061abc	11.03ab	367.05ghi	0.22de	753.31ab
T+MPR+AS	6.0ef	4.6gh	0.6f	0.007c	11.99a	321.2ij	0.22de	629.77a
T+MPR+TSP	6.5ab	5.3bcd	0.4g	0.039bc	11.82a	465.01bc	0.2e	599.98a
Cambisol								
Control	5.6h	4.8fg	1.1de	0.102abc	4.09efg	397.78efg	0.225de	3947.11de
T	5.6gh	4.8fg	1.3c	0.175a	2.51gh	413.8defg	0.32bc	3987.21de
T+MPR	5.8fg	4.7fgh	1.3c	0.102abc	4.45ef	384.49fgh	0.26cde	3275.41cd
T+TSP	5.5h	4.7fgh	1.3cd	0.144ab	6.37cd	477.21b	0.27cd	3395.84cde
T+MPR+AS	5.5h	4.5h	1.2cd	0.084abc	3.18fgh	397.06efg	0.27cd	2801.87c
T+MPR+TSP	5.6h	4.6fgh	1.3c	0.105abc	3.75efgh	423.03cdef	0.27cd	3448.6cde

T: Tithonia, MRP: Minjingu rock phosphate, AS: Ammonium sulphate, TSP: Triple superphosphate, pH_w=pH water, AV.P=Available P

Means with different letter in each single column are significantly different between treatments and soil types at (P < 0.05) Duncan's multiple range tests.

In the mixture+lime, the pH_w of control was higher than those of other treatments at the end of the experiment and this was due to the low biomass produced on control which could

have mined less bases compared to other treatments. The organic C increased in treatments than control with higher increases in treatment T+MPR+S and T+TSP as a result of tithonia incorporation as green manure. The total N decreased in all treatments with exception to the treatments that received ammonium sulphate and the one with T+MPR which had produced little biomass. Available P increases were higher in all the treatments than control, with significant increases in treatments T+MPR+AS and T+TSP; with percentage increases of 242.3% and 89.6% , respectively. Total P increases due to treatments were higher than control except for treatment T. Exchangeable K showed slight increase above control ($0.21 \text{ Cmol}_c \text{ Kg}^{-1}$) while for total K, only treatment T+MPR had higher increase above control.

For pegmatite, the pH_w of control was lower than those of other treatments at the end of the experiment and this was due to tithonia application which increased base cations in the substrate. The organic C at the end of the experiment did not increase due to treatments but decreased compared to the onset levels. The total N did not differ among treatments but generally decreased compared to the levels before planting. Available P increases were significantly higher in all the treatments than control, with higher increases in treatments T+MPR+AS and T+MRP+TSP; with percentage increases of 281.8% and 276.4% respectively. Total P increases due to treatments were higher than control for all treatments. Exchangeable K showed high increase above control ($0.09 \text{ Cmol}_c \text{ Kg}^{-1}$) as well as total K.

In the cambisol, the pH_w of all treatments was generally the same except for the treatment T+MRP which had a slight increase of 3.6% over the control. The organic C slightly increased in treatments than control. The total N at the end of the experiment did not significantly change across treatments but generally decreased compared to the value at onset of the experiment. Available P did not generally increase over the control except for the treatment of T+MRP and T+TSP which had percentage increase of 8.8% and 55.7% respectively. Total P increases due to treatments were generally higher than control.

Exchangeable K showed slight increase above control ($0.225 \text{ Cmol}_c \text{ Kg}^{-1}$) while for total K, only treatment T had higher increase above control.

Table 9 shows the actual changes of soil chemical properties at the end of the field experiment. The Table shows that on pegmatite, all treatments showed a decrease in total N after the experiment with the exception of the control and the treatment of tithonia+MRP+AS. This shows that continuous farming on technosol with no input results in N negative balance (Varco, 1999; Gan *et al.*, 2003). With the treatment that received AS, the decline in total N could have been caused by high nitrates leaching (Van Straaten, 2002), ammonia volatilization and high N uptake by soybean due to the pegmatite's low CEC (5.6), it is sandy texture with a relatively high pH water (5.9) compared to the average highland soil pH in Rwanda (60% of lands are covered by soils with pH less than 5.5).

There was generally an increase in all treatments in available P, exchangeable K, organic C and pH on all the soil types subsequent to the incorporation of organic resources and mineral fertilizers (Malama, 2001; Hedlund *et al.*, 2003; Diogo *et al.*, 2009).

Table 9: Changes in soil chemical properties after the field experiment in Gatumba Mining District

Treatments	pH	N (%)	P (ppm)	K (cmol/kg)	C (%)
Pegmatite					
Control	0.9	-0.1025	2.44	-0.03	-0.31
T	0.9	-0.099	8.91	0.09	-0.31
T+MPR	1.25	-0.096	9.53	0.11	-0.31
T+TSP	0.8	-0.049	10.33	0.1	-0.21
T+MPR+AS	0.6	-0.103	11.29	0.1	-0.11
T+MPR+TSP	1.1	-0.071	11.12	0.08	-0.31
Mixture					
Control	1.3	-0.026	1.42	0.09	0.29
T	1.2	-0.012	1.69	0.24	0.69
T+MPR	1.5	0.006	4.51	0.22	0.49
T+TSP	1	-0.052	5.55	0.35	0.99
T+MPR+AS	0.9	0.07	6.77	0.19	1.19
T+MPR+TSP	1	-0.1085	3.32	0.22	0.59
Cambisol					
Control	0.6	-0.008	3.39	0.105	0.39
T	0.6	0.065	1.8	0.2	0.59
T+MPR	0.5	-0.008	3.75	0.14	0.59
T+TSP	0.5	0.034	5.67	0.15	0.59
T+MPR+AS	0.3	-0.026	2.48	0.15	0.49
T+MPR+TSP	0.45	-0.005	3.05	0.15	0.59
p value	<0.001	<0.001	<0.001	<0.001	<0.001
SED	0.0972	0.05258	0.809	0.02609	0.0847

T: Tithonia, MRP: Minjingu rock phosphate, AS: Ammonium sulphate, TSP: Triple superphosphate

4.2 Response of Soybean performance to various experimental treatments

4.2.1 Soybean growth performance in the Greenhouse and in the Field

Soybean plants grew quite well in the greenhouse throughout the whole growing season without showing any signs of nutrient deficiency or toxicity except for those which

were growing on the mixture. Soybeans growing on the mixture showed some slight chlorotic symptoms with dead spots an indication of manganese toxicity which, however, disappeared after 25 days of planting. The low pH KCl (3.9) of the mixture and poor drainage of the soil because of high clay content might have enhanced toxicity of elements such as manganese due to anaerobic situation in soil.

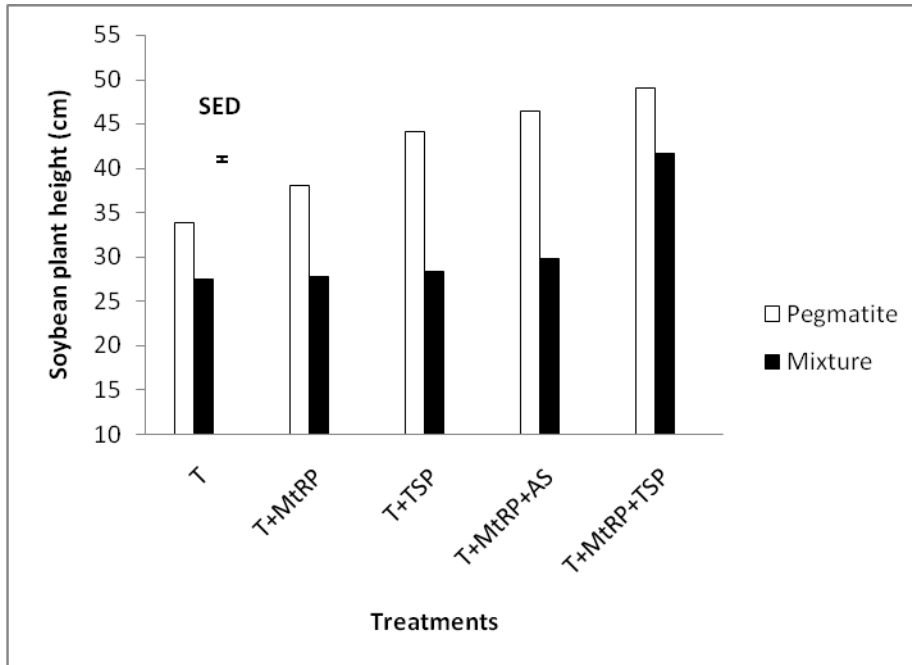
In the field, soybean grew well throughout the short rains season of 2011 except for the control which showed nutrient deficiency symptoms for N (lower leaves were chlorotic or pale green) and P deficiency (necrotic spots and purple colour with the older leaves). This could be due to low contents of N and p in soil (See Table 7) (Grundon, 1987; Havlin *et al.*, 1999).

4.2.2 Soybean plant height

The results for soybean plant heights in the greenhouse (January 2012) and field experiments during the 2011 SR are presented in Figures 5 and 6. Figure 5 presents Greenhouse soybean heights while Figure 6 presents field heights.

The Greenhouse height results reveal that soybean grown in the pegmatite substrate was significantly ($p < 0.05$) taller than in the mixture. The treatment of T+MtRP+TSP showed higher heights on both pegmatite and mixture (49.04cm and 41.67cm respectively). This could have been caused by a good supply of P through enhancement of the MtRP agronomic effectiveness through mixing it with water soluble phosphates (TSP). Chien *et al.* (1987) showed that small amounts of water-soluble phosphates act as a starter dose for the plants until P from the phosphate rock becomes available to the plants. This initial starter dose of water-soluble P stimulates dense root system development which then increases the utilization of the remaining phosphate rock (Chien *et al.* 1996). The addition of ammonium sulphate also increased soybean plant heights on both pegmatite and mixture. However, there

was no significant increase in heights on the mixture for all the treatments except for T+MtRP+TSP.

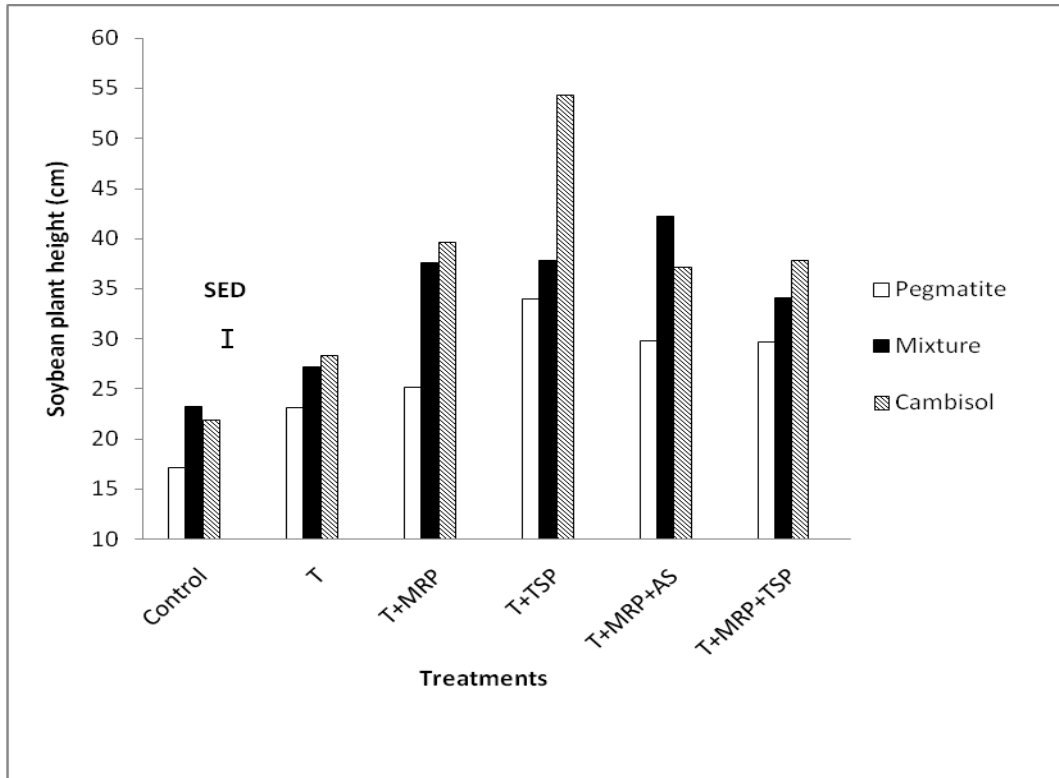


T: Tithonia, MtRP: Matongo rock phosphate AS: Ammonium sulphate, TSP: Triple superphosphate. SED is presented to compare plant height among soil types within each treatment

Figure 5: Soybean plant height at harvest in the Greenhouse during the 2011 short rains season

In the field (Figure 6), the height of soybean plants growing in the mixture was higher although not significantly ($p < 0.05$) different to the ones grown in pegmatite. The highest height attained by the mixture was 40 cm under treatment T+MRP+AS. Soybean heights in cambisol were generally higher than the two technosols except for the treatment of T+MRP+AS where the mixture surpassed. The highest height on cambisol was 54.37 cm on T+TSP. The addition of highly soluble P source (TSP) increased considerably the soybean height especially on cambisol. This is in agreement with results of Gardener (1979) who

found that when P is supplied in total amount required, the N fixing plants increase in height and biomass even on mine spoils.



T: Tithonia, MRP: Minjingu rock phosphate, AS: Ammonium sulphate, TSP: Triple superphosphate. SED is presented to compare plant height among soil types within each treatment

Figure 6: Soybean plant height at harvest in the field during the 2011 short rains season

4.2.3 Soybean number of pods and nodules

Soybean number of pods in the greenhouse experiment

The results for the number of pods in the greenhouse (January 2012) are presented in Table 10 below. The number of pods per soybean plant was significantly higher ($p < 0.01$) on pegmatite than on the mixture in all the treatments. For both pegmatite and mixture, the highest pod number per plant (9.3) was obtained on the treatment Tithonia+ MtRP +TSP and the lowest on Tithonia alone and Tithonia + MtRP.

Table 10. Soybean number of pods and nodules per plan in the greenhouse at NUR

Treatment	Number of pods	Number of Nodules
Pegmatite		
T	5.7	21.2
T+MtRP	5.0	18.9
T+TSP	7.0	34.4
T+MtRP+AS	6.0	27.4
T+MtRP+TSP	9.3	30.7
Mixture		
T	4.3	4.9
T+MtRP	4.3	5.1
T+TSP	4.7	10.6
T+MtRP+AS	5.3	5.6
T+MtRP+TSP	5.7	7.9
SED	0.694	3.3

T: Tithonia, MtRP: Matongo rock phosphate, AS: Ammonium sulphate, TSP: Triple superphosphate. SED is presented to compare soybean pod and nodule number among soil types within each treatment.

The number of soybean pods were lower in both pegmatite and mixture substrates used in the greenhouse experiment compared to the values obtained in the cambisol field trial. The nodule numbers in cambisol in field experiment were higher than in the mixture but less than in pegmatite (both technosols in the greenhouse experiment).

Soybean number of nodules in the greenhouse experiment

The average number of nodules in the different treatments across different soil types in the greenhouse experiment is presented in table 10. Soybean grown on pegmatite showed highest number of nodules compared to the mixture. The treatment of Tithonia+TSP recorded the highest number of nodules (34) compared to other treatments while tithonia+MtRP recorded the lowest number of nodules (5). The higher number of nodules recorded on treatments that received TSP was due to the favourable effect of P which is required for

energy generation and for the normal functioning of nitrogen fixing bacteria (Khan *et al.*, 2000).

Table 11. Soybean number of pods and nodules per plant in the field during the 2011 short rains season

Treatment	Number of pods	Number of Nodules
	Pegmatite	
Control	5.67	15.17
T	21.33	20.75
T+MRP	17.33	16.92
T+TSP	19.92	31.42
T+MRP+AS	20.92	31.50
T+MRP+TSP	30.17	20.17
	Mixture	
Control	12.08	2.67
T	24.75	3.42
T+MRP	18.08	5.08
T+TSP	28.17	9.5
T+MRP+AS	22.33	4.58
T+MRP+TSP	27.75	4.92
	Cambisol	
Control	8.17	4.83
T	14.08	6.25
T+MRP	16.50	7.83
T+TSP	23.17	12.58
T+MRP+AS	21.33	8.58
T+MRP+TSP	15.08	8.58
SED	3.309	3.26

Tithonia, MRP: Minjingu rock phosphate, AS: Ammonium sulphate, TSP: Triple superphosphate. SED is presented to compare soybean pods number among soil types within each treatment

Soybean number of pods in the field experiment

The soybean numbers of pods and nodules in the field experiment during the 2011 SR are presented in Table 11. The soybean number of pods per plant was significantly higher (<0.05) for the mixture than for pegmatite with the exception of treatment Tithonia + TSP+

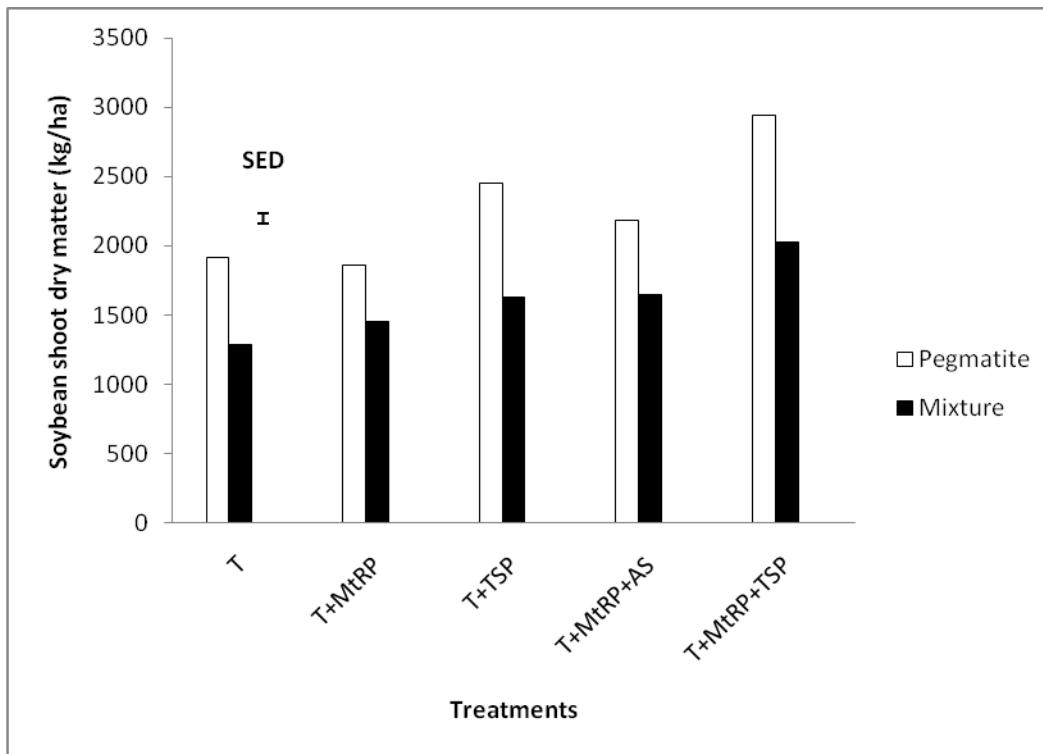
MRP, while for the cambisol, the number of pods were generally low but bigger in size and all filled with grains than those from the other soil substrates. The higher number of pods observed on the treatments that received TSP in all the soil types is explained by the important role of P in the physiological process of pod formation in the plant. Khan *et al.* (2000) reported significant increase of pod formation by soybean after P application

Soybean number of nodules in the field experiment

The soybean grown on pegmatite showed the highest number of nodules compared to the mixture and the cambisol in field experiments. The treatment of Tithonia+TSP recorded the highest number of nodules (31.5) among treatments in the 3 types of soils while the control had the lowest number of nodules in all soil types. There was a highly significant difference (<0.01) in the number of nodules between soybean grown on pegmatite and those grown on the mixture and between different treatments in the field experiments. However, there were no significant differences (<0.05) between number of nodules recorded on the mixture and the ones recorded on cambisol.

4.2.4 Soybean shoot dry matter yield

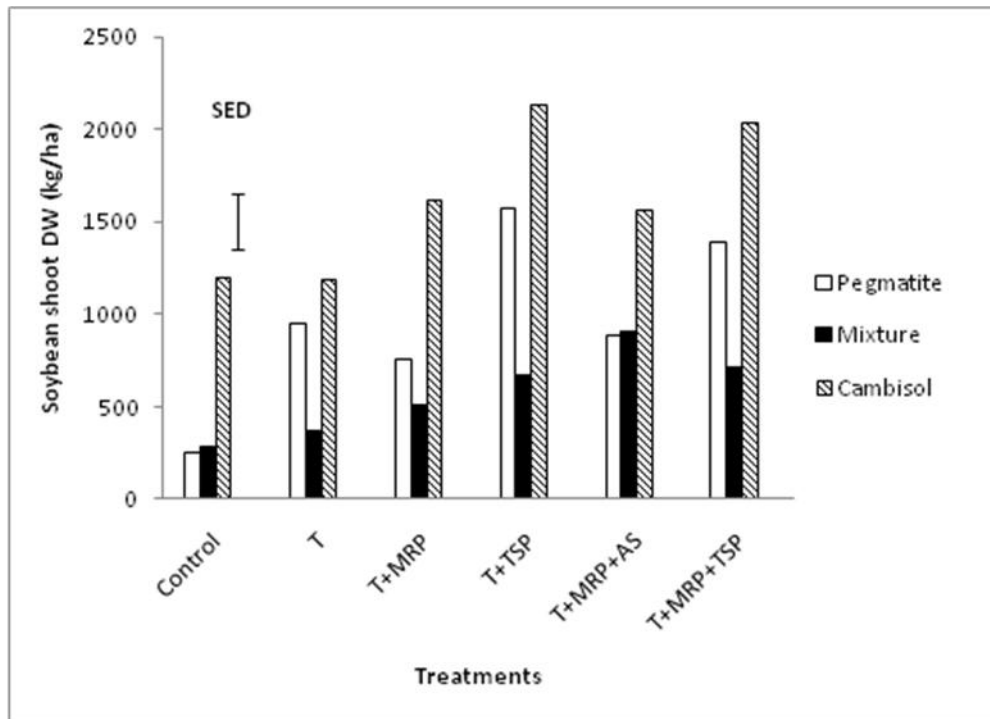
The soybean shoot dry weights in different treatments across different soil types are presented in Figure 7 for the greenhouse. All treatments showed higher soybean shoot dry weights in pegmatite than in the mixture. This could have been caused by better soil nutrients availability on pegmatite than on the mixture. The better aeration of the sandy pegmatite than the mixture rich in clay could have favoured higher decomposition of tithonia and less P and NH_4^+ fixation by clays (Nieder *et al.*, 2010; Khan *et al.*, 2000; Yamauchi, 1993; Fageria *et al.*, 2006).



T: Tithonia, MRP: Minjingu rock phosphate, AS: Ammonium sulphate, TSP: Triple superphosphate. SED is presented to compare soybean pods number among soil types within each treatment

Figure 7: Soybean shoot dry matter at harvest in the greenhouse

Figure 8 shows shoot dry matter in the soil substrates in the field experiment. The application of water soluble P source (TSP) showed higher increase in shoot dry matter production in both greenhouse and field experiments (Khan *et al.*, 2000; Shabayev, 1991). Cambisol recorded highest shoot dry matter weights than the two technosols with the highest weight of 2200kg ha⁻¹ obtained by treatment T+TSP followed closely by treatment T+MRP+TSP (2000Kg ha⁻¹)(Figure 6.b). The soybean biomass produced in pegmatite and Mixture in the greenhouse was higher than the values of soybean biomass received on cambisol in the field experiment.

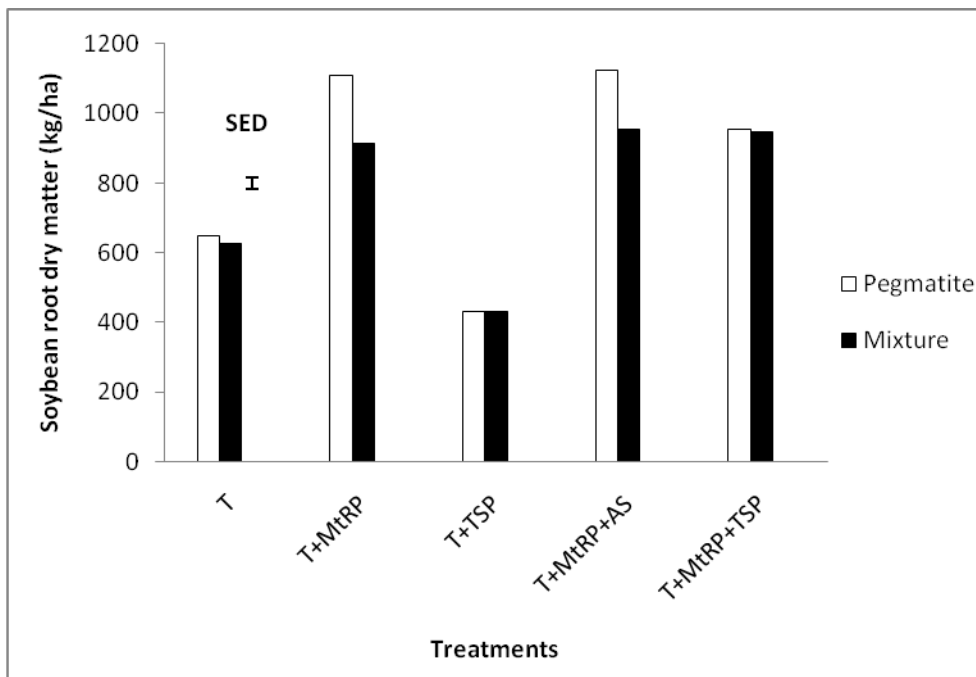


T: Tithonia, MRP: Minjingu rock phosphate, AS: Ammonium sulphate, TSP: Triple superphosphate. SED is presented to compare soybean shoot dry weight among soil types within each treatment

Figure 8: Soybean shoot dry matter at harvest in the field experiment during the 2011 short rains season

4.2.6 Soybean root dry matter

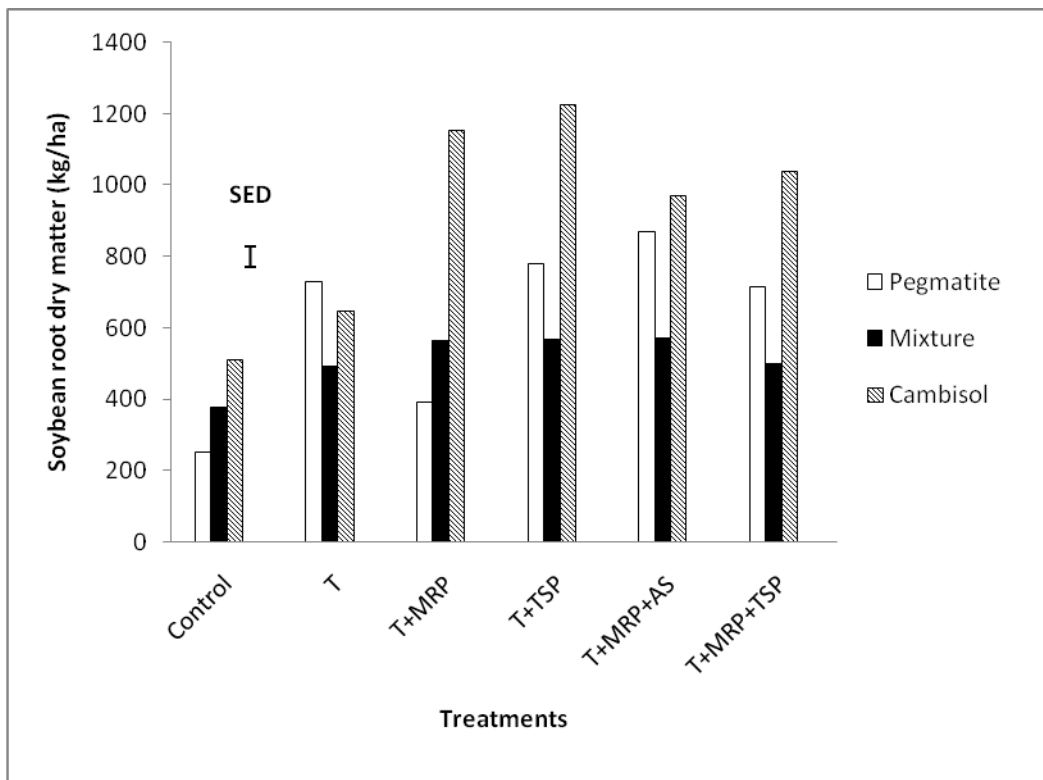
The results of soybean root dry matter for the greenhouse experiment (January 2012) are presented in Figure 9. In comparison, the root heights in pegmatite were slightly longer than those of the mixture. This could be explained by the good drainage and better aeration of the sandy texture of pegmatite in addition to its neutral pH that might have neutralised the aluminium concentration in soil, thus favouring good root growth (Roberts *et al.*, 2012).



T: Tithonia, MtRP: Matongo rock phosphate, AS: Ammonium sulphate, TSP: Triple superphosphate. SED is presented to compare soybean root dry matter among soil types within each treatment.

Figure 9: Soybean root dry matter at harvest in the greenhouse

In the field experiment, soybean root dry weight was relatively higher in pegmatite than in the mixture with the exception of the control (Figure 10). The soybean root dry matter recorded on cambisol was consistently higher ($p < 0.05$) than the two technosols. Since good root systems are the pump and vessels that supply water, nutrients and hormones for growth and good development of plant, the good rooting systems observed on soybean grown on cambisol and pegmatite explains the higher grain and shoot dry matter yield obtained in these soils (Iijima *et al.*, 1991; Yamauchi, 1993; Grzesiak *et al.*, 2002; Masle, 2002; Fageria *et al.*, 2006). The cambisol as one of the predominant reference soil groups in Gatumba and which is not affected by mining, showed higher root dry weight compared to the two technosols from coltan mining.



T: Tithonia, MRP: Minjingu rock phosphate, AS: Ammonium sulphate, TSP: Triple superphosphate. SED is presented to compare soybean root dry matter among soil types within each treatment

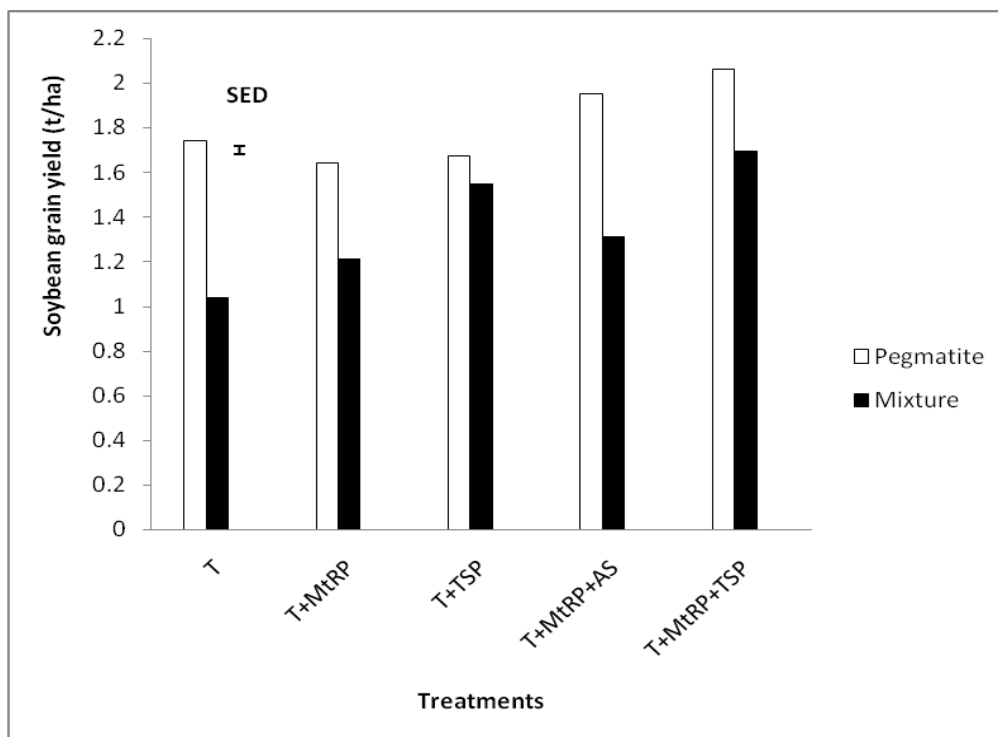
Figure 10: Soybean root dry matter at harvest in the field experiment during the 2011 short rains season

4.2.7 Soybean grain yield

The soybean grain yield in the greenhouse (January 2012) is presented in Figure 11. All the treatments showed significant ($p < 0.01$) higher soybean grain yields on pegmatite than on the mixture. The treatment of tithonia+MtRP+TSP recorded the highest grain yield (2.06 t ha^{-1}) followed closely by Tithonia+MtRP+AS (1.95 t ha^{-1}).

The significantly higher soybean grain yields ($p < 0.01$) obtained on pegmatite substrate compared to pegmatite-Lixisol B₁ mixture as seen in Figure 11, could be explained by the lower pH levels of the mixture which might have reduced microbial activity, increased

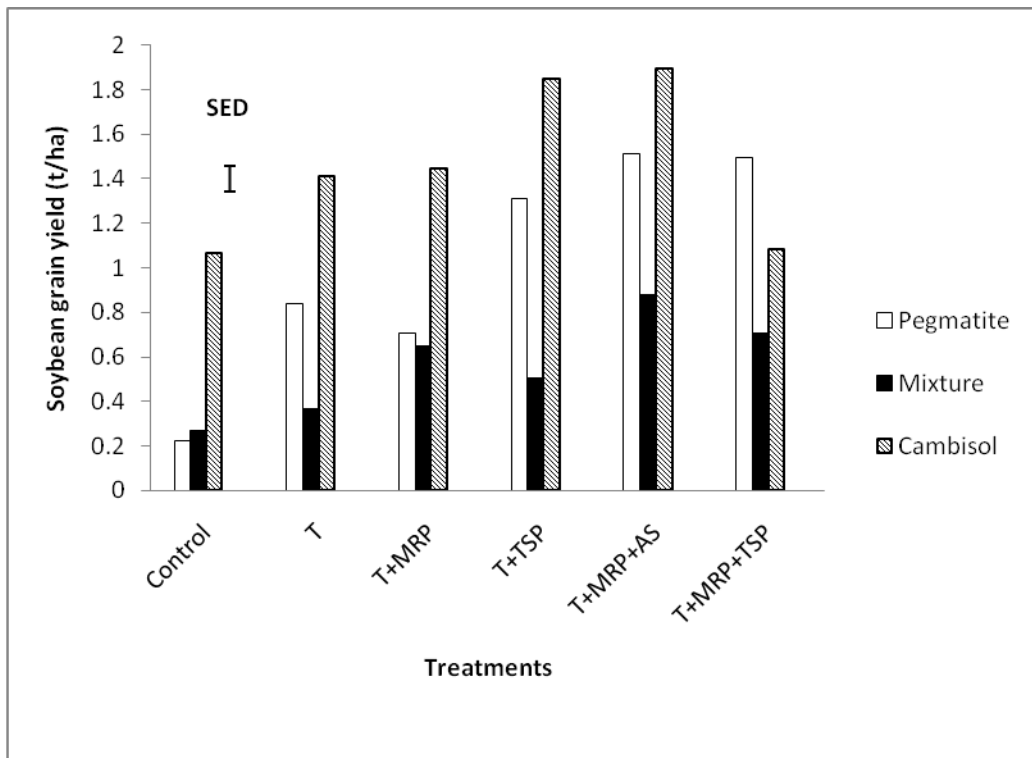
Al availability and caused immobilization/ fixation of phosphates. There was no significant difference ($p < 0.05$) in soybean grain yield between the treatment that received Tithonia+MRP+TSP and the one that received Tithonia+MRP +AS despite the relatively high amount of N added. Gardiner (1979) reported that P was the only nutrient which limits the growth of nitrogen-fixing legume species on mine rock. Many studies have reported no yield increase of soybean grain when N fertilizers are applied and they assumed that the crop simply substitutes the N it ordinarily would have derived from BNF with N from fertilizer (Deibert *et al.*, 1979, Barker and Sawyer, 2005; Gan *et al.*, 2003; Schmitt *et al.*, 2001), Early application of even small amounts of N often results in temporary suppression of nodule establishment and subsequent activity (Hungria *et al.*, 2005).



T: Tithonia, MtRP: Matongo rock phosphate, AS: Ammonium sulphate, TSP: Triple superphosphate. SED is presented to compare soybean grain yield among soil types within each treatment.

Figure 11: Soybean grain yield at harvest in the greenhouse

Soybean grain yield in the field experiment is presented in Figure 12. All the treatments showed significantly ($p < 0.01$) higher soybean grain yields in cambisol than in the two technosols (pegmatite and mixture). The treatment of tithonia+MRP+AS gave the highest soybean grain yield (1.9 t ha^{-1}) followed closely by tithonia+TSP treatment (1.85 t ha^{-1}) in cambisol. The cambisol which is not affected by mining was more fertile than the two technosols (Pegmatite and mixture). Higher grain yield in pegmatite was recorded in the treatment of Tithonia+MRP+AS treatment (1.5 t ha^{-1}) followed closely by tithonia+MRP+TSP (1.49 t ha^{-1}).



T: Tithonia, MRP: Minjingu rock phosphate, AS: Ammonium sulphate, TSP: Triple superphosphate. SED is presented to compare soybean grain yield among soil types within each treatment

Figure 12: Soybean grain yield at harvest in the field experiment during the 2011 short rains season

Higher soybean grain yield harvested in the pegmatite compared to the mixture could have been caused by favourable soil conditions especially pH levels (6.7 to 7.3) while the

mixture had lower pH water (5). These findings are generally in agreement with those of Ann *et al.* (2009) who confirmed that except for P, which is more easily available within a pH range of 6 to 7, macronutrients (N, K, Ca, Mg, and S) are more available within a pH range of 6.5 to 8, while the majority of micronutrients (B, Cu, Fe, Mn, Ni, and Zn) are more available within a pH range of 5 to 7. Moreover, the high clay content, due to the presence of “high activity clays” in the B_t of Lixisols (Reetsch *et al.*, 2007) might have caused fixation of K⁺ and NH₄⁺ and rendered them inaccessible by plants (Nieder *et al.*, 2010).

The relatively higher soybean grain yield observed in pegmatite treated with only tithonia than in pegmatite treated with tithonia and MRP was probably due to the Ca²⁺ released by tithonia during decomposition. This might have increased the Ca²⁺ concentrations in the soil solution, hence increased the pH, thereby reducing the rock phosphate solubility through mass action. Karanja *et al.* (2004) observed similar reduction of P solubility of the more reactive Mijingu rock phosphate upon addition of tithonia biomass. Zaharah and Bah (1997), also observed a similar decrease in the solubility of the reactive Algerian rock phosphate following incorporation of green manures.

4.3 Nutrients uptake by soybean

4.3.1 Nutrients accumulation by soybean in the greenhouse experiment

The above ground (AG) soybean biomass accumulation of N, P and K were significantly (<0.05) higher on pegmatite than on the mixture (Table 12). The combination of Tithonia, MtRP and TSP had the highest N, P and K accumulation (225.59 kg N ha⁻¹, 10.66 kg P ha⁻¹, 69.46 kg K ha⁻¹) followed by the treatment of T+MtRP+AS (216.2 kg N ha⁻¹, 8.46 kg P ha⁻¹, 60.42 kg K ha⁻¹), whereas N and P accumulation in the T+MtRP on pegmatite (142.19 kg N ha⁻¹, 7.08 kg P ha⁻¹) and Tithonia alone on the mixture (94.2 kg N ha⁻¹, 4.62 kg P ha⁻¹) were the lowest. Highest N and K content in roots were observed in the T+MRP+AS treatment whereas highest P content occurred in T+MRP on pegmatite substrate. For the

mixture, the highest root N content was observed in treatment T+MRP+AS, highest P accumulation in T+MRP and K in T+MRP+TSP. At the same time, the mixture showed the lowest root content in N and K whereas the lowest root P accumulation occurred in T+TSP treatment. In general, pegmatite substrate yielded higher nutrient accumulation than the mixture for both above ground and root biomass.

Table 12: Above ground (AG) soybean plant and root biomass nutrient accumulation at harvest in the greenhouse experiment

Treatment	AG nutrient accumulation (kg ha ⁻¹)			Nutrient accumulation in roots (kg ha ⁻¹)		
	N	P	K	N	P	K
PEGMATITE						
T	151.10 c	8.48 b	78.16 a	18.6 cd	0.77 bcd	4.47 b
T+MtRP	142.19 c	7.08 cd	64.09 bc	20.3 cd	1.62 a	11.97 a
T+TSP	179.29 b	10.70 a	60.80 c	11.9 d	0.81 bcd	3.32 b
T+MtRP+AS	216.23 a	8.46 b	60.42 c	40.0 a	1.16 b	12.07 a
T+MtRP+TSP	225.59 a	10.66 a	69.46 b	30.7 abc	1.10 b	11.92 a
MIXTURE						
T	94.28 d	4.62 f	33.51 e	20.2 cd	0.52 cd	2.42 b
T+MtRP	135.77 c	5.58 ef	38.97 e	28.4 abc	0.95 bc	3.12 b
T+TSP	173.72 b	7.73 bc	49.09 d	10.7 d	0.40 d	3.85 b
T+MtRP+AS	136.11 c	6.23 de	51.93 d	34.4 ab	0.77 bcd	3.60 b
T+MtRP+TSP	173.64 b	7.63 bc	64.67 bc	25.9 bc	0.84 bcd	4.03 b

T: Tithonia, MtRP: Matongo rock phosphate, AS: Ammonium sulphate, TSP: Triple superphosphate. Means with different letter in each single column are significantly different between treatments at ($P < 0.05$) using Duncan's multiple range tests. AG nutrient accumulation includes accumulation from grains and shoots.

4.3.2 Soybean nutrient accumulation in the field experiment

Table 13 shows the soybean nutrient accumulation from the field trial as segmented in 3 parts of the plant; the grain, the shoot and the root. Above ground nutrient accumulation included the shoots and the grains. More N, P and K accumulations were found in the grains as expected. In general, soybean grown on pegmatite had relatively higher N, P and K accumulations than the mixture and the cambisol.

Table 13: Soybean grain and shoot nutrient accumulation at harvest during 2011 short rain in the field experiment

Treatment	Grain nutrient accumulation(kg ha ⁻¹)			Shoot nutrient accumulation(kg ha ⁻¹)		
	N	P	K	N	P	K
Pegmatite						
Control	12	0.72	1.41	3.3	0.4	1.67
T	52.2	5.23	9.87	19.45	4.79	16.69
T+MRP	24.2	2.55	4.37	10.61	2.67	8.97
T+TSP	43.2	4.72	8.81	10.45	6.41	16.00
T+MRP+AS	27.5	3.00	5.27	8.3	3.97	9.53
T+MRP+TSP	31.1	3.13	6.08	6.29	2.13	8.18
Mixture						
Control	11.4	0.84	1.55	2.61	0.17	0.78
T	20.1	1.15	2.09	5.23	0.26	1.74
T+MRP	23.7	2.12	3.81	5.85	0.34	2.74
T+TSP	28.6	1.85	3.07	4.7	0.57	2.98
T+MRP+AS	40.8	2.91	4.89	7.1	0.6	4.02
T+MRP+TSP	32.9	2.30	4.18	10.03	0.92	4.4
Cambisol						
Control	36	3.32	6.55	6.78	0.36	1.97
T	68.2	5.98	11.03	13.25	0.99	8.63
T+MRP	54	4.61	8.19	12.01	0.73	5.64
T+TSP	70.6	6.51	11.39	12.82	2.02	6.15
T+MRP+AS	52.5	4.5	8.08	10.26	0.54	6.34
T+MRP+TSP	37.9	3.58	6.40	6.24	0.42	3.58
p value	0.039	0.024	0.016	0.007	<.001	0.012
SED	10.11	0.962	1.768	3.023	0.834	2.65

T: Tithonia, MRP: Minjingu rock phosphate, AS: Ammonium sulphate, TSP: Triple superphosphate. SED: Standard error of differences between means

Table 14: Soybean above ground (AG) and root nutrient accumulation at harvest during 2011 short rain in the field experiment

Treatment	AG nutrient accumulation(kg ha ⁻¹)			Nutrient accumulation in roots (kg ha ⁻¹)		
	N	P	K	N	P	K
Pegmatite						
Control	15.3	1.12	3.09	6.62	0.555	3.23
T	71.6	10.02	26.56	11.54	1.929	13.04
T+MRP	34.8	5.22	13.35	5.81	1.447	6.87
T+TSP	53.6	11.14	24.81	12.2	2.582	15.43
T+MRP+AS	35.8	6.96	14.8	9.59	1.968	11.91
T+MRP+TSP	37.4	5.26	14.26	7.61	1.601	8.39
Mixture						
Control	14	1.02	2.32	2.32	0.189	1.08
T	25.3	1.41	3.83	2.96	0.256	2.61
T+MRP	29.5	2.45	6.55	3.39	0.265	2.66
T+TSP	33.3	2.42	6.04	2.42	0.339	3.28
T+MRP+AS	47.9	3.52	8.91	0.73	0.291	2.57
T+MRP+TSP	42.9	3.22	8.58	4.17	0.229	3.44
Cambisol						
Control	42.8	3.69	8.52	8.7	0.417	1.78
T	81.4	6.97	19.66	6.52	0.498	5.53
T+MRP	66.1	5.33	13.84	5.93	0.75	6.15
T+TSP	83.4	8.54	17.54	8.3	1.323	5.12
T+MRP+AS	62.8	5.04	14.42	8.82	0.583	5.75
T+MRP+TSP	44.2	4	9.98	5.18	0.668	3.92
p value	0.039	0.01	0.021	<.001	<.001	<.001
SED	13.03	1.736	4.357	1.388	0.2387	1.457

T: Tithonia, MRP: Minjingu rock phosphate, AS: Ammonium sulphate, TSP: Triple superphosphate

4.3.3 Nitrogen accumulation by soybean at maturity stage in both greenhouse and field experiments

The combination of tithonia green manure and different inorganic fertilizers in both greenhouse and field experiments significantly increased the N accumulation by soybean (above ground and root biomass) compared to tithonia alone (Tables 12 and 14). The treatments T+MRP+TSP and T+MRP+AS which had the highest N accumulation were not significantly different. This shows that soybean could be grown without mineral N fertilizers when N is provided by tithonia green manure and when P is continuously supplied by the combination of the rapid P releasing mineral fertilizer (TSP) and slow P releasing rock phosphate. The highest soybean N accumulation was recorded with the T+MRP+TSP treatment in all the soil types used. This could be an indicator of higher nitrogen fixation by soybean when good sources of P are provided. Similar results were reported by Basir *et al.*, (2005), Salvagiotti, (2008) and Sarawg *et al.*, (1999) who found higher N uptake due to good supply of P that seemed important for Rhizobium to fix relatively more nitrogen in soils. This led to increased plant growth and N uptake by root and then translocated to shoots.

Lower N accumulation on the mixture soil could also be explained by the potential constrained N₂ fixation process by soil acidity (Parker and Harris, 1977). The reduced N accumulation from the mixture compared to pegmatite could be due to ammonium fixation in 2:1 clay mineral and the formation of organic-mineral complexes on clay mineral and fine silt surfaces (Nieder *et al.*, 2010).

Low N accumulation in plant tissues could also be partly due to the low rate of tithonia decomposition and mineralization under acidic and high clay content conditions of the mixture soil. Better root proliferation, good availability of N due to favourable pH (6.3), and good soil moisture and aeration under pegmatite substrates led to higher N uptake in all treatments. This is in agreement with the findings of Purcell (2004) who found higher N

fixation by soybean when no moisture stress was experienced. Parker (1977) also found high soybean N fixation when pH was almost neutral. In general, all treatments that received the combination of mineral (especially P) and organic (tithonia) fertilizers showed higher N accumulation than the control. This is in agreement with the findings of Bandyopadhyay (2010) who observed higher soybean N uptake in integrated organic and mineral fertilizer treatments.

4.3.4 Phosphorus accumulation by soybean at maturity stage in both greenhouse and field experiment

In both greenhouse and field experiments, the phosphorus accumulation by soybean plant tissues as shown in Tables 12 and 14 was higher in pegmatite than in the mixture which had low P availability and low pH values. This low pH might have increased solubility of aluminium and iron complexes, releasing their ions into soil solution, which may have readily reacted with water-soluble P to form less soluble and more stable compounds (Boland *et al.*, 2006; Naidu *et al.*, 1990).

The higher P uptake observed from T+MRP+TSP treatment could be due to the enhancement of agronomic effectiveness of low reactive PR blended with water-soluble phosphate (TSP). The probable explanation for this interaction is that the initial effect caused by the water-soluble P, might have led to higher P plant uptake from PR enhanced by the better rooting system. This is in agreement with the findings of Chien *et al.* (1987) who showed that small amounts of water-soluble phosphates act as a starter dose for the plants until P from the PR becomes available to the plants. This technique, with various nutrient blending ratios, has shown promising results in many agronomic tests in sub-Saharan Africa (Chien *et al.* 1987, 1996; Govere *et al.* 1995; Van Straaten *et al.*, 1995; Mnkeni *et al.* 2000).

4.3.5 Potassium accumulation by soybean at maturity stage in both greenhouse and field experiments

The K accumulation by soybean plant tissues in both greenhouse and field experiments is shown in Tables 12, 13 and 14. The observed higher K accumulation in pegmatite soil than in the mixture could be partly explained by K fixation in the high clay content of the mixture (43.2%). Rowell (1981) reported that some potassium is found within secondary clay mineral structures such as illite, vermiculite and chlorite, and is released slowly. The lower K accumulation in the mixture could have been caused by higher K fixation in the illite (4.6%) and Montmorillonite (3.1%) clay minerals present in the Lixisol of GMD (Appendix 5). This reduced K accumulation with the mixture could also be explained by the progressive compaction of this substrate by continued watering. This is in accordance with Lipiec *et al.* (1995) who found reduction of K uptake by soybean in compacted soil and who mostly attributed it to the decrease in root surface area. Greater K influx per unit root surface in a compacted soil without K application was not sufficient to compensate for reduced K concentration due to restricted root growth of soybean seedlings (Hallmark and Barber, 1981). Wolkowski (1991) in his review mentioned that K uptake may be reduced where root respiration is significantly reduced as a result of reduced soil aeration. On the mixture, higher K accumulation was found with the treatment that had higher root and shoot biomass (T+MRP+TSP) and this could be due to the soybean dense roots which mined K that was normally fixed in the clay interlayer of the mixture. Van Straaten (2002) reported that roots and rhizospheres of plants are active biological weathering agents that transform micas and release K and other cations.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

The first objective of the study was to evaluate the suitability of two technosol substrates (pegmatite and pegmatite-Lixisol B_t mixture from the GMD) on soybean performance in the greenhouse. After the greenhouse experiment, it was observed that technosol substrates could give even higher yields than some of the unmixed soils used by farmers (e.g. cambisol).

The second objective was to determine and compare the effects of incorporated tithonia leaves and different inorganic fertilizers to Technosol on soybean production and plant nutrients uptake (N, P, and K). The greenhouse and field experiments results showed that the incorporation of tithonia and different fertilizers increased significantly the soybean biomass and the plant N, P and K uptake. Phosphorus inputs were found essential to increase yields since they enhanced the biological nitrogen fixation. The treatments that received AS were found not to be significantly different ($p < 0.05$) from the ones that received only tithonia in combination with different forms of phosphorus.

On the third objective, which was to determine the effects of the degraded soils of GMD on soybean performance in the field, the study indicated that pegmatite performed better than its mixture with Lixisol B_t. Pre-cropping soil analyses showed that the mined soils were extremely poor in nutrients and that there was no organic carbon in the pegmatite substrate. Even in the pegmatite-Lixisol B_t mixture, the organic matter content was very low (0.1% C). The observed increase of soil carbon during the growth period in almost all treatments, and the yield obtained in the treatment where only tithonia biomass (5t ha⁻¹) had been incorporated show that tithonia may not only be a useful source of plant nutrients but also a source for the formation of soil organic matter.

Technosols in mining areas are very poor in plant nutrients but have the potential for agricultural use if reclaimed. The pegmatite substrate was more effective in soybean production than its mixture with Lixisol B_t material. *Tithonia diversifolia* with its high nutrient status is a potential soil improver for enhanced productivity. The treatment Tithonia + MRP + TSP was an effective source of P compared to TSP or MRP alone since it gave the best grain yields and the highest crop N, P, and K accumulation in most of the soil substrates used.

The GMD technosol materials showed great agricultural potential which could be positively exploited if their storage capacity of nutrient and water is improved. In the long term, the mixture of pegmatite and Lixisol B_t could be expected to increase the SOM accumulation (mineral-organic complexes), the CEC as well as the water holding capacity. Since P adsorption occurs mainly under acid soil conditions, liming could be an option for remobilization of P, and so the application of lime should be recommended as it increases the pH of the soil mixture. The long-term effect of lime could also contribute to the degradation of organic matter, reducing the solubility of toxic minerals (Al and Fe from lixisol B_t) and improving the texture of the soil.

5.2 Recommendations

Based on the findings of this study, farmers should be encouraged to use tithonia as green manure especially in combination with mineral P sources to improve soybean yields on technosols from GMD and other similar areas. Farmers should be encouraged to use the combination of Tithonia (5t DM ha⁻¹) and TSP (50kg P ha⁻¹) for them to boost up production above current yields of 1.05t/ha. .

This study, nevertheless, didn't cover all the related gaps due to limitation of time and resources. More research, therefore, needs to be carried out in GMD on the potential of these

technosols since they have shown some improving qualities (near neutral pH, high total P and K) not even found in the normally farmed soils in the region. In this study, only one level of mixture (pegmatite+Lixisol B_t 1:1) was investigated. There is need for more research to be done to find out the proper mixture levels that can increase water holding capacity, organic matter accumulation and soil CEC without increasing the P and NH₄⁺ fixation by clays.

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APPENDICES

Appendix 1: Field experimental layout

Block 1	Control	T1	T3	T5	T4	T2
Block 1	T4	T3	T2	Control	T5	T1
Block 1	T3	Control	T5	T2	T1	T4
Block 2	T1	T5	T2	T3	T4	Control
Block 2	T5	T1	Control	T4	T2	T3
Block 2	T3	Control	T4	T2	T5	T1
Block 3	T4	T2	Control	T1	T3	T5
Block 3	Control	T4	T1	T5	T2	T3
Block 3	T2	T3	T5	T1	Control	T4

T1: Tithonia

T2: Tithonia+Minjingu Rock Phosphate

T3: Tithonia+TSP

T4: Tithonia+Minjingu Rock Phosphate+Ammonium Sulphate

T5: Tithonia+Minjingu Rock Phosphate+ Triple Superphosphate

Appendix 2: Calculations

Total N in soil samples

Calculations:

$$\% \text{ N in soil sample} = ((a-b) \times 0.1 \times v \times 100) \div (1000 \times w \times al)$$

Where a= volume of the titre HCl for the blank, b= volume of the titre HCl for the sample, v= final volume of the digestion, w= weight of the sample taken and al= aliquot of the solution taken for analysis.

Source: (Okalebo *et al.*, 2002).

CEC Calculations

Calculations:

$$\text{CEC (meq/100g)} = \text{NH}_4\text{-N} + (\text{mg/L as N}) \div 14 + (\text{NH}_4\text{-N in extract} - \text{NH}_4\text{-N in blank})$$

Note:

If NH₄-N is expressed as mg/L of NH₄, not NH₄- N, divide the result by 18 instead of 14 to obtain CEC.

Source: (Okalebo *et al.*, 2002).

Appendix 3: Summary of soil chemical data interpretation

Interpreted values	Mean values of the analysis	Soil classes and/ or qualification
pH water	>8,5	Very high
	7,0 - 8,5	High
	5,5-7,0	Medium
	<5,5	Low and very low
CEC (meq/100g)	>40	Very high
	25-40	High
	15-25	Medium
	5-15	Low
	<5	Very low
Exchangeable Bases (en meq/100g)		
Calcium	>10	High
	4-10	Medium
	<4	Low
Magnesium	>4	High
	4-0,5	Medium
	<0,5	Low
Potassium	>0,6	High
	0,6-0,2	Medium
	<0,2	Low
Sodium	>1	High
	0-1	Medium
	0	Low
Organic carbon in %	>10	High
	4-10	Medium
	<4	Low
Total Nitrogen (Kjeldahl) in %	>0,5	High
	0,2-0,5	Medium
	<0,2	Low
Available Phosphorus in ppm (Bray 1, advised for acid soils)	>50	High
	50-15	Medium
	<15	Low

Source: Landon J-R (1991)

Appendix 4: Soybean plants sown in large containers in the greenhouse



Appendix 5: Clay mineral contents in B horizons of soils from Gatumba mining district

Location	Soil unit / horizon	Montmorillonite	Illite	Kaolinite
		%	%	%
Buranga	Gleysol (in alluvial material) / Bg1	25.1	24.9	50.0
	Acrisol / IIBt	42.6	27.2	30.1
	Acrisol / IIIBt	8.3	7.2	84.5
Nganzo	Fluvisol 2/ B1	5.5	19.8	74.7
	Fluvisol 2/ B2	6.2	19.3	74.5
	Fluvisol 2/ Bg	20.1	32.9	47.0
	Gleysol (on mine spoil) / Bg	2.5	9.0	88.6
	Cambisol (overlying Gleysol) / Ah/Bw	4.2	27.8	68.0
	Nitisol / B1	2.6	3.8	93.5
	Nitisol / B2	25.8	5.2	69.0
	Nitisol / B2	25.8	5.2	69.0
Rongi	Cambisol 1 / Bw	9.0	18.6	72.4
	Cambisol 2 / Bw	2.9	30.1	67.0
Nyamisa	Nitisol / Bw1	3.0	9.0	88.1
	Nitisol / Bw2	1.9	11.8	86.3
	Colluvium / Ah/Bw	9.2	24.6	66.2
	Cambisol (in Colluvium) / Bw	6.2	3.7	90.1
	Lixisol / Bt	3.1	4.6	92.3
	Lixisol / Bw	8.0	6.5	85.5
	Anthrosol 2	1.2	3.7	95.1

Source: Reetsch, 2008