# RESPONSE OF FOUR ROBUSTA COFFEE (*Coffea canephora*) VARIETIES TO NITROGEN, PHOSPHORUS AND POTASSIUM

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**A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF REQUIREMENTS FOR THE DEGREE OF MASTERS OF SCIENCE (SOIL SCIENCE AND LAND MANAGEMENT) OF THE SOKOINE UNIVERSITY OF AGRICULTURE. MOROGORO, TANZANIA.**

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# ABSTRACT

The study aimed at identifying the best varieties among the four Robusta coffee varieties in terms of N, P and K nutrients use efficiency, absorption efficiency and translocation efficiency. First, a survey was conducted to determine the fertility status of the coffee growing areas in eight villages namely Igomba, Kiilima, Katangalala, Mishozi, Katale, Bugabo, Bulinda and Bugaruka. Then, a screen house pot experiment was conducted in a Completely Randomized Design in a 3x4 factorial scheme with three rates of N, P and K; Urea (0, 150, 300 kg N/ha equivalent to 0, 75, 150 mg N/kg of soil), TSP (0, 75, 150 kg P/ha equivalent to 0, 37.5, 75 mg P/kg of soil) and KCl (0, 150, 300 kg K/ha equivalent to 0, 75, 150 mg K/kg of soil) and four Robusta coffee varieties (MR 10, BK 27, ML 2 and 13/61). After 6 months, the whole plants were uprooted, washed and roots separated from the aerial parts for determination of shoot dry matter and root dry matter, and N, P and K contents in the whole coffee plants. Nutrient use efficiency, nutrient absorption efficiency and nutrient translocation efficiency for N, P and K were calculated. Results indicated that the overall soil fertility status of the surveyed areas were generally low, with low pH ranged from 4.12 to 5.53, organic carbon ranged from 0.09% to 2.25%, total nitrogen range from 0.056 to 0.192 %, available P ranged from 20.21 to 68.29 mg/kg and potassium ranged from 0.11 to 1.81 cmol (+) kg$^{-1}$. The varieties MR 10, BK 27 and 13/61 are most efficient in low nitrogen. Varieties BK 27 and 13/61 are most efficient in low soil P and K. Varieties which are more responsive and efficient to absorb translocation and use the added nutrients' elements and hence can adapt to low soil fertility areas are BK 27, 13/61 and MR 10. In order to improve the production level of coffee in Kagera, distribution of the most responsive varieties should be the first priority.

# DECLARATION

I, Almas Hamadi, do hereby declare to the Senate of Sokoine University of Agriculture that this research dissertation is the result of my own original work done within the period of registration, and that it has neither been submitted nor being concurrently submitted for degree award in any other institution.

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# DEDICATION

The author dedicates this dissertation in memory of his mother, the late Salma Athumani, and to his father, the late Hamadi Juma Mshihiri, and his entire family including his wife Ashura Mussa and son Abdul Almas. Their support, patience and thoughtfulness are grate- fully acknowledged.

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# LIST OF ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| AE | Absorption Efficiency |
| ARI | Agriculture Research Institute |
| BK | Bukoba |
| CAN | Calcium Ammonium Nitrate |
| CBD | Coffee Berry Disease |
| CEC | Cation Exchange Capacity |
| CLR | Coffee Leaf Rust |
| CRD | Completely Randomized Design |
| CWD | Coffee Wilt Disease |
| ER | Effective and Responsive |
| ESP | Exchangeable Sodium Percentage |
| FAO | Food and Agriculture Organization |
| ha | Hectare |
| K | Potassium |
| KAE | Potassium Absorption Efficiency |
| KCl | Potassium Chloride |
| kg | Kilograms |
| KTE | Potassium Translocation Efficiency |
| KUE | Potassium Use Efficiency |
| masl | Meter above sea level |
| ML | Muleba |
| MR | Maruku |
| N | Nitrogen |
| NAE | Nitrogen Absorption Efficiency |

| | |
|---|---|
| NER | Non-efficient and Responsive |
| NTE | Nitrogen Translocation Efficiency |
| NUE | Nitrogen Use Efficiency |
| NUE | Nutrient Use Efficiency |
| OC | Organic carbon |
| P | Phosphorus |
| PAE | Phosphorus Absorption Efficiency |
| PTE | Phosphorus Translocation Efficiency |
| PUE | Phosphorus Use Efficiency |
| RDM | Root Dry Matter |
| SDM | Shoot Dry Matter |
| TaCRI | Tanzania Coffee Research Institute |
| TDM | Total Dry Matter |
| TE | Translocation Efficiency |
| TSP | Tri super phosphate |
| Var. | Variety |

# CHAPTER ONE

## 1.0 INTRODUCTION

All the commercial coffee species which are cultivated today are believed to have originated from Africa and belong to the genus *Coffea* (DaMatta, 2007). Coffee (genus *Coffea*) is widespread throughout the tropics with more than 70 species under cultivation (Pohlan, 2010). The important coffee species today are *Coffea arabica* (Arabica, 64% of world production) and *Coffea canephora* (var. Robusta, 35% of world production) (Pohlan, 2010). Coffee is among the most important agricultural commodities on the world market, and it is cultivated worldwide on approximately 10.3 million hectares and represents the sole economic income for more than 25 million families worldwide (Maro, 2010).

Coffee (Arabica and Robusta) is currently Tanzania's most important export crop and has been one of the three most important cash crops since the early colonial period (Raikes, 2015). While sisal was grown entirely on plantations and cotton solely by smallholders, coffee has been produced by both, however with very few large estates mainly for the Arabica type (Raikes, 2015). The crop is produced and exported by more than 60 nations and ranks as one of the top cash crops in the developing countries, Tanzania inclusive (Pohlan, 2010).

Robusta coffee, (*Coffea canephora*) is one of the dependable and important cash crops for more than 250,000 families in Kagera Region in the western part of Tanzania (TaCRI, 2006). It accounts for 30 to 50% of the coffee production in Tanzania and contributes about 20 to 25% of the national foreign exchange earnings from coffee sales both for the export and internal markets (TaCRI, 2008). Robusta coffee grows well in high rainfall areas (2200 to 3000 mm/year), warmer temperature (18 to 36 °C) and medium altitude areas (Coffee chemistry, 2015). In Tanzania, robusta coffee is mainly cultivated in Karagwe, Muleba, Misenyi, Bukoba, Ngara and Biharamulo districts, Kagera Region. In all these districts coffee is grown on top of the hill ridges running north-south and parallel to Lake Victoria. This is because these locations are the only suitable land for coffee cultivation with enough rainfall, fairly fertile soils and good temperature (TaCRI, 2008).

For optimal coffee growth, development and productivity, nutrients must be available in the soil in sufficient and balanced quantities so as to meet the nutrient requirement by the coffee plants (Chen, 2006). The current yield level of coffee in Tanzania is approximately 50 000 tons per year, both Robusta and Arabica coffee (Magomba, 2012). The most important constraint to high coffee yields in developing countries, and especially among resource-poor farmers, is the low fertility status of the soils in the areas where coffee is grown (Mohamadi and Sohrabi, 2012). The majority of the soils in Kagera Region, where coffee is grown are acidic (pH < 5.1) with low nitrogen and phosphorus (Maro, 2011). High rainfall regimes in areas along and near the Lake Victoria shores coupled with poor soil management practices, have contributed to soil erosion problems in these areas hence soil and land degradation (RCO Kagera, 1998). Although most of the soils in Kagera are of low fertility status, the majority of the farmers don’t use fertilizers or manures (RCO Kagera, 1998), hence, compounding the problems associated with soil fertility decline. In some areas where intercropping with some legumes and application of manures is being practiced the problem of N has been somehow reduced but not that of phosphorus and potassium (Maro, 2011).

The production levels of coffee as well as the quality of the coffee in Kagera are on the decline due to low soil fertility caused by inappropriate soil management (Maro, 2011).

The major plant nutrients that determines yield and quality of coffee are N, P and K. Nitrogen improves vegetative growth and the capacity of coffee plants to bear large coffee beans (Amaral, 2012). Phosphorus in Robusta coffee enhances roots and bearing wood development, early berry maturity and bean density (Maro, 2011). Coffee plants also have high demand for potassium as it is essential for many plant functions such as enzyme activity, the transport of water, nutrients and sugars and control of stomata cells (Sobip, 2014). Thus, optimum supply of these nutrients from the soil is essential for enhanced and sustainable coffee growth and production.

Plant nutritional requirements and plant growth vary according to species and cultivar (Martinez *et al*., 1993; Fageria, 1998), depending on the efficiencies of nutrient uptake (Duncan and Baligar, 1990; Sands and Mulligan, 1990; Swiader *et al*., 1994), translocation (Li *et al*., 1991), and its role in plant nutrition (Siddiqi and Glass, 1981; Sands and Mulligan, 1990). Several factors like gene constitution which are related to morphological and physiological plant characteristics contribute to an efficient nutrient use by coffee plants (Li *et al*, 1991). Morphological characteristics such as extensive root system, a close relation between roots and canopy, the ability of the root system to modify the rhyzosphere contribute to the efficiency of a plant for uptake and nutrient use (Fageria and Baligar, 1993).

Reduced soil fertility has been enhanced by the application of fertilizers coupled with good agricultural practices and management which results in increased rates of plant production and costs (Martins *et al*., 2013). In this percepective, the optimization of coffee nutritional efficiency is critical to increase productivity and reduce the cost of agricultural production systems (Martins *et al*., 2013). The nutritional efficiency of plants is conditioned by numerous factors and the growing environment. The factors include, root parameters related to nutrient uptake, shoot-root relations and root-soil interaction (Sauerbeck, 1990). Therefore, the knowledge of the genetic basis and mode of inheritance can assist in selecting coffee genotypes with desirable agronomic characteristics coupled with nutritional efficiency and genetic variability (Martins *et al*., 2013). The need of expanding agricultural production with reference to coffee has increased interest in the use of genotypes with the potential to adapt to adverse conditions of soil fertility (Martins *et al*., 2013). In this sense, optimization of nutritional efficiency of the coffee would potentially contribute to enhanced and sustain coffee productivity, both in terms of increased yields and quality of the coffee (Lima *et al*., 2003).

Appropriate soil fertility management for improved coffee productivity involves both appropriate plant nutrient applications and the plant’s ability to absorb and utilize the applied nutrients (Sopib, 2014). This means nutrient use efficiency should be part and parcel of the soil fertility management packages in coffee production. Nitrogen, potassium and phosphorus management in coffee grown in Tanzania is still not well developed and addressed, especially in terms of improving their use efficiency (UE) by the coffee plants. As a result smallholder farmers in Kagera Region are reluctant to invest in the use of fertilizers in coffee production because of the very low returns to the fertilizers applied.

In Kagera Region, the programme for improved Robusta coffee varieties was established in 2001. The program focused on developing improved Robusta coffee varieties which are high yielding and resistant to diseases, especially coffee wilt disease (CWD). So far about four Robusta coffee varieties, namely Bukoba 27 (BK27), Muleba 2 (ML2), Maruku 10 (MR10) and 13/61 have been released that have high yield potentials and resistant to diseases like CWD and coffee leaf rust (CLR) (Kilambo, 2012). However, the aforementioned strategy has not taken on board their optimal nutrient requirements and their nutrient use efficiencies.

The nutrient use efficiencies by Robusta coffee plant are related to rates of absorption, translocation and utilization of the nutrients by the plants (Ahmad *et al*., 2001). Generally, under the same conditions, crop varieties respond differently to the plant growth factors and this is due to variations in growth and nutritional requirements of the plants (i.e. genetic and phenotypic characteristics). The present study was an attempt to assess and identify the best genotypes of Robusta coffee already distributed to farmers in Kagera Region, which can adapt to limited nutritional conditions as an attempt to establish the most economic N, P and K rates. The specific objectives were to;

i. Determine the fertility status of the soils in the Robusta coffee growing areas of Bukoba rural
ii. Determine the response of the four Robusta coffee varieties to different rates of N, P and K in terms of N, P and K uptake (contents) by the plants
iii. Determine the best varieties with high N, P, and K nutrient use efficiency (NUE), absorption efficiency (AE) and translocation efficiency (TE)

# CHAPTER TWO

## 2.0 LITERATURE REVIEW

### 2.1 Historical Background of Coffee

Coffee is a plantation crop which is adapted to tropical highlands (especially for Arabica) and to low lands (especially for Robusta). It is believed that all commercial coffee species both Arabica and Robusta originated from central Africa (Hermann, 2010). Coffee cherries then moved from Central Africa to the Arabian Peninsula and were cultivated in what is now called Yemen. In Yemen, they used the skin of the cherry to make a sort of tea. It was not until early 1700 that the Dutch introduced it, first in Java, Indonesia and from there it spread quickly all over the world including Tanzania (Kuit, 2004).

Coffee may have been introduced to Tanzania in the 16th century from Ethiopia. Rather than being brewed to produce a beverage, they were initially chewed as a stimulant (amwani). The Haya tribe came to use coffee beans as money during marriage, and coffee growing could only be authorized by tribal leaders. Under the German colonialization, coffee began to be cultivated as a cash crop. The Germans weakened the control of the tribal leaders over coffee growing, thereby allowing for a more widespread propagation of coffee plantations. Coffee (Arabica) was, firstly, introduced in Kilimanjaro by Catholic missionaries in the year 1898, and the first variety to be introduced was Bourbon and Kent (TCB, 2010). For Robusta coffee, oral history indicates that the Haya tribe brought coffee from Abyssinia (now called Ethiopia) during the 16th century in which they called it *amwani* and they used it for transaction with other commodities rather than consumption (TCB, 2005).

## 2.2 The Economic and Nutritional Importance of Coffee

Coffee is one of the world's most popular beverages. After oil, coffee is the second most traded commodity in the world (Hlio, 2013). Coffee is an important source of export earnings to many nations, including Tanzania. It accounted for approximately US$ 16.5 billion in the global economy in 2010 (TaCRI, 2006). The world production is currently estimated to reach over 130 million 60-kg bags. Brazil and Vietnam are the major coffee producers and together represent slightly less than half of world's coffee production volume. Africa produces about 12% of the world volume. Tanzanian share is less than one percent (0.6% in 2011) of the world production (TCB, 2012).

Extensive and intensive research on coffee has been undertaken for more than a century and claims a number of health benefits. Research indicated that a daily cup of coffee may reduce the risk of type 2 diabetes, Alzheimer's disease and also is powerful antioxidants (Gabrick, 2009). Coffee contains a stimulant called caffeine, which is the most commonly consumed psychoactive substance in the world, and this can help people feels less tired and also increases the energy level (Gunnars, 2013).

## 2.3 Coffee Production Trends in Tanzania

Since the mid-1990s, the Tanzanian coffee industry has been in a state of stagnation or decline and the major the reason being the falling of the world coffee price (TaCRI, 2006). Average yearly coffee production in Tanzania over the past thirty years has stagnated at a level of about 50,000 tons, while yields have continuously decreased, and quality potential has not been fully exploited (TCB, 2012). About 90% of the national production is usually exported, and the remaining 10% is sold in the internal market, mainly to the processing industries (TCB, 2012).

Tanzania is endowed with abundant land with appropriate altitude, temperature, rainfall and soil suitable for high-quality Arabica and Robusta coffee production. The major Arabica growing regions is the Kilimanjaro / Arusha, Mbeya, and Mbinga/Ruvuma. Robusta is mainly produced in the Kagera Region. Other coffee growing regions include Tanga, Iringa, Morogoro, Kigoma, Manyara, Mwanza, Rukwa and Mara (TCB, 2012). Low coffee production is generally due to factors like continuous deteriorating of soil fertility, effect of climate change, outbreak of diseases and pests and low price of coffee in the world market and poor participation of youth in coffee production (Baliger, 1998). Furthermore, in Tanzania the decline in coffee production has been attributed to the very high production costs, mostly associated with the very high prices of pesticides and inorganic fertilizers (TCB, 2012).

## 2.4 Coffee Breeding/Improvement Strategies in Tanzania

Since 2002, the Crop Improvement Department (CID) of the Tanzania Coffee Research Institute continued with its meticulous breeding programme to develop, evaluate and propagate high-yielding CLR and CWD resistant varieties with good bean size and cup quality, for Robusta coffee (TaCRI, 2006). Coffee wilt disease is among many socio-economic and technical constraints encountered by Robusta coffee growers, which threaten the long-term survival of the Tanzanian coffee industry (Carr, 2003). Since the first outbreak of Coffee Wilt Disease in 1997 in Kagera, a breeding programme at the Tanzania Coffee Research Institute has been in progress (Kilambo, 2012). The breeding program gradually increased in complexity (that is from single to multiple and back crosses) in an effort to recombine all the required characteristics of disease resistance, yield and quality in one genotype. The four coffee wilt disease resistant varieties and high-yield Robusta genotypes were proposed (TaCRI, 2008) and it was officially released in 2012. However, there is no any recommended fertilizer rates documented, and there is a need first to analyze the efficiency of these varieties on nutrient elements absorption, translocation and use.

## 2.5 Growing Conditions and Requirement for Robusta Coffee

Robusta coffee, consequent to its central African origin, is the best adapted to less elevated, hot and humid forest of tropical regions (Hermann, 2010). Robusta coffee (*C. canephora*) is a coffee plant grown on tropical lowlands (below latitude 10°) up to elevation of 1000 m above sea level. Robusta coffee requires high temperatures and higher moisture than the *C. arabica* (Koitsaar, 2011). The crop is preferably grown between 15° N and 12° S in flat areas and elevations between 300 and 800 masl, and the optimum annual mean temperature ranges from 22 to 30°C (Hermann, 2010). For the rainfall, Robusta coffee, because of its shallow root system can, tolerate rainfall over long periods (more than 3000 mm) and high soil moisture, but requires a short dry season to initiate massive flowering (Hermann, 2010).

## 2.6 Nitrogen, Phosphorous and Potassium Nutrition and Requirements by Robusta Coffee (*Coffea canephora*)

### 2.6.1 Nitrogen requirements by coffee

The demand and importance of N by coffee plants had been known since the early 1950s (Maria, 2006). Nitrogen requirement increases with plant age, especially at the beginning of coffee cherry production (Catani and Moraes, 1958). If there are no other limiting factors present, an adequate N supply will promote rapid plant development (Uchida, 200). This is specifically through the increase in the number of leaf pairs and plagiotropic branches per plant, number of nodes per branch, and number of fruiting nodes and flowers per node, which, taken together, are associated with higher yields in coffee (Malavolta, 1986; Willson, 1985; Fahl *et al*., 1994; Nazareno *et al*., 2003). In addition, N is a decisive factor for the protection of coffee plants against photo inhibition of photosynthesis when plants are exposed to high radiation, because it promotes the triggering and reinforcement of protective mechanisms (Nunes *et al*., 1993; Fahl *et al*., 1994; Ramalho *et al*., 1999; 2000). All of these plant growth components together, results in higher coffee yields (Maria, 2006).

For the production of 1,850 kg/ha of berries, coffee requires 160 kg N/ha and 50 kg P/ha in deep, well-drained, loamy or volcanic soils of Kenya (Haifa, 1999). In Cote d'Ivoire production of 1000 kg/ha of coffee requires 85.2 kg N/ha/year (FAO, 2013). The differences in yield are due to farming systems, awareness of farmers on the use of fertilizers and the country's coffee production policy (FAO, 2013).

The nitrogen deficiency symptoms in coffee are characterized at first by general chlorosis of the young leaves; later, older leaves also became chlorotic, resulting in the entire plant having a pale green to yellow-green appearance (Nagao, 1986). In India, it was discovered that when one ton of green been harvested from the coffee tree, approximately 40 kg nitrogen (N) must be replaced yearly (FAO, 2014). Generally, a mature coffee plant requires about 200 to 300 kg N/ha in a year (Sopib, 2014).

### 2.6.2 Phosphorus requirement by coffee

Phosphorus is a component of many cell constituents and plays a major role in photosynthesis, respiration, and energy storage and transfer, cell division, and cell enlargement (Mullins, 2009). Adequate phosphorus is needed for the promotion of early root formation and growth (Mullins, 2009). Phosphorus also improves crop quality and is necessary for seed formation (Mullins, 2009). P deficient coffee plants are characterized by a slight mottled chlorosis of the older leaves, and later the older leaves became more chlorotic, with faint interveinal yellowing (Nagao, 1986). In the advanced stages, necrotic spots developed on the leaves (Nagao, 1986). The critical concentration of P in coffee plant tissues ranges from 0.12 to o.2 % (Ctahr, 2000). P deficiency in coffee impare plant growth through stunted root growth which later affects the absorption capacity of nutrients and this result into dwarf and early maturity of the coffee cherries and hence poor quality (Sopib, 2014). The net effect of phosphorus deficiency is a decrease in coffee yields and quality. Coffee plant requires approximately of 2.3 kg of P per year to produce one ton of clean coffee (Titus, 2006).

### 2.6.3 Potassium requirements by coffee

Coffee plants have a high demand for potassium (200 to 300 kg K/ha/year). It has been reported that potassium has an irreplaceable part to play in the activation of enzymes, which are fundamental to metabolic processes, especially the production of proteins and sugars (Sopib, 2014). Potassium is also the “plant-preferred” ion for maintaining the water content and hence the rigidity of each cell, a biophysical role which helps the plant to prevent it from drying (Sopib, 2014). Potassium deficiency symptoms in coffee are localized in older leaves and first will appear as a chlorotic band along leaf margins. Later, dark-brown necrotic spots can develop along the leaf margins. The necrotic spots would continue to enlarge until the entire margins are necrotic, with the central portion of the blade remaining green (Nagao, 1986). The critical concentration of K in coffee plant tissues ranges from 2.00 to 2.50% K (Ctahr, 2000). Potassium deficiency in coffee can reduce the disease resistance of the plant, formation of cherries and reduce the plant’s resistance to soil moisture deficit, thus affecting the yield and quality of coffee (Mancuso, 2014). Coffee plant requires 15 kg of K per annum to produce one ton of clean coffee (Titus, 2006).

## 2.7 Concepts of Nutritional Efficiency

The term nutritional efficiency in plants is used to characterize the plant's ability to absorb and utilize plant nutrients (Martins, 2015). Nutritional efficiency is also related to economic output (yield) per unit fertilizer applied (Baligar and Fageria, 1998). Physiological nutritional efficiency is related to the efficiency of a genotype to absorb nutrients from the soil, distribute it and use it internally (Goddard and Hollis, 1984). The genotypic differences in nutritional efficiency are attributed to several factors that are related to the absorption, transport and utilization of nutrients by plants (Marschner, 1995). These genotypic differences involved in the mineral nutrition of plants can be explained by morphological and physiological aspects related to the absorption of nutrients (Gabelman and Gerloff, 1983).

Coffee genotypes or varieties can be categorized into "effective" and "ineffective" (Vosse, 1987), or "non responsive" in relation to dry matter production (Blair, 1993; Ciat, 1978; Fox, 1978; Amaral *et al*., 2012; Martins *et al*., 2013; Christo *et al*., 2014). Clones characterized as effective and responsive (ER) are those producing high yields in conditions of low plant nutrient elements in the soil and, also respond to the increase of the nutrient elements in the soil (Amaral *et al*., 2012). Clones characterized as non-efficient and responsive (NER) are those with significant production at low levels of plant nutrient elements in the soil, but they respond less in terms of yield or dry matter yield to the increase in nutrient elements in the soil (Amaral *et al*., 2012). Li *et al*. (1991) defined the plant nutritional efficiency as a product of acquisition efficiency and use efficiency of the nutrients by plants. The acquisition efficiency includes the absorption mechanism efficiency and the intensity of fine root growth while the use efficiency is a measure of the efficiency of the transport and production of biomass per unit of nutrient absorbed (Malavolta, 2002).

The nutrient use efficiency indices can be calculated as suggested by Siddiqi (1981) where Nutrient Use Efficiency (NUE) = (total dry matter yield) $^2$ / (total plant nutrient). The uptake efficiency indices are calculated as reported by Swiader (1994) that is (total plant nutrient content) / (root dry matter). The translocation efficiency indices are calculated as Translocation efficiency = 100 x (nutrient content in the aerial part) / (total plant nutrient content) (Li *et al.*, 1991).

## 2.8 Nitrogen, Phosphorous and Potassium Use Efficiency by Coffee Plants

In tropical soils, phosphorus (P) is the nutrient that limits the biomass production the most, due to its strong interaction with the soil components hence reduced availability of inherent and applied P (Lima, 2002). For increased coffee production, P has to be applied to soils hence increasing the coffee production cost which is a major limitation in the coffee production systems under small-scale coffee production (Amaral *et al.*, 2012). Thus, the nutritional efficiency of P should be prioritized in order to increase the efficiency of this nutrient in crops and reduce the use of unnecessary high rates of phosphate fertilizers (Lima, 2002). In order to increase P acquisition efficiency, three strategies can be applied, molecular assisted plant breeding, genetic engineering and the use of appropriate agricultural practices (Ramaekers, 2001). Molecular assisted plant breeding strategies, including developing cultivars that are superior in P acquisition and higher yielding in P deficient conditions through plant breeding (Zhang *et al.*, 2007; Fageria *et al.*, 2008; Hammond *et al.*, 2008). Genetic engineering, including transferring specific genes from other species, which are more efficient to P while use of the state of the art agricultural practices, including inoculation of rhizobia (Ramaekers, 2001).

Potassium in soil can be thought of as existing in four “pools” related to its availability to plants. These pools are the soil solution K, which it is immediately available for uptake by roots, the readily available K pool, the slowly available K pool and the soil K minerals, which is least available (Johnston, 2013). When more potassium is added in manures and fertilizers than is used by the crop, potassium ions move from the soil solution to the readily available and slowly available pools. This reversible transfer of potassium between these pools is very important in crop nutrition and soil fertility (Johnston, 2013).

## 2.9 Varietal Effect on Nutrient Use Efficiency in Coffee

Under the same cultivation conditions, coffee varieties behave differently with the manifestation of different growth and productivity responses. Such behavior may be due to differences in nutrient use among varieties (Malavolta, 2002). Differences in nutrient use efficiencies between genotypes may be related to the demand for the nutrients at the cellular level, the affinity of the absorption system, compartmentalization in roots or other plant organs, the mobility in the xylem and phloem vessels and changes in the rhizosphere during growth (Marschner, 1995). Baligar and Fageria (1999) summarized the features related to plant nutritional efficiency as absorption, translocation, and nutrient utilization efficiencies. However, the usage efficiency of a particular nutrient reflects not only the content of the nutrient in different organs at a given nutritional condition, but also the amount of dry matter produced per unit of nutrient acquired.

## 2.10 Soil Factors Affecting Nitrogen, Phosphorous and Potassium Use Efficiency in Coffee

### 2.10.1 Soil temperature

One of the important environmental factors affecting plant growth and nutrient response by crops is soil temperature. Nitrogen availability from the soil can be affected through effects on mineralization of soil organic matter and organic fertilizers and nitrate leaching (Agostini *et al.*, 2010). Low soil temperature depresses P availability and plant uptake through reducing the rate of mineralization of soil organic P because of lowered microbial activity (Better crops, 1999). Soil temperature also affects the availability of K in the soil, especially row K which is important when temperature is low, especially for early planted and minimum tilled crops (Better crops, 1999).

### 2.10.2 Soil moisture

One of the most singled out problems in agriculture is either the lack or excess of soil moisture. The internal transport of nutrients largely depends upon the synthesis, utilization and translocation of photosynthates and this can only be aided by adequate soil moisture (Misra, 1982). Phosphorus becomes more mobile and less adsorbed to minerals in waterlogged conditions while nitrogen is denitrified by changing form from a liquid to a gas which can be lost to the atmosphere (USDA, 1997). Moisture is needed for root growth through the soil to “new” supplies of N, P and K. It is needed for mass-flow movement of N, P and K to the plant roots with water and for the diffusion of N, P and K to the roots to resupply those taken up by the roots (Better crops, 1999).

### 2.10.3 Soil chemical properties

Soil pH has an important role in P availability and affects the efficiency of applied P. Phosphorus fixation by Fe and Al oxides is greatest in acid soils, but declines as soils are limed (Better crops, 1999). The organic matter in the soil not only supplies different nutrient elements after decomposition, but also improves the physical conditions of soils such as soil texture, porosity and soil structure (Malavolta, 2002). Organic matter also stimulates microbial activity, protects the soil from erosion, retards the fixation of nutrients and increases the buffering capacity of soils. This is because the organic matter improves total soil porosity, influence water-holding capacity of the soil and regulates the soil temperature. The above benefits in turn increase the nutrient uptake efficiency of the applied nutrients (Marschner, 1995).

## 2.11 Approaches to Improve NUE by Coffee Plants

Various studies have been made on genes, genotypes and breeding approaches aimed at improved nutrient use efficiency (NUE). Nutrient use efficiency is not a trait of a genotype, but a characteristic of the crop or the cropping systems which are determined by the interaction between genotype, environment and agricultural management (Kristensen, 2013). Nutritional efficiencies include efficiency on absorption, translocation and use of absorbed nutrient elements. Efficiency of nutrient absorption may be acquired through several ways, including an adequate geometry and distribution of the root structure, and system which helps to improve nutrient absorption efficiency (DaMatta, 2007). Rhizosphere environment coupled with chemical changes in the root zone also increases absorption efficiency, presence and activity of mycorrhizae, tolerance of the variety to conditions of low pH and response of the genotype under low nutrient supply (Souza, 1994; Fageria, 1998; Fageria and Moreira, 2011).

The efficiency on the translocation of the absorbed nutrients through the roots and their release into the xylem involve several steps that limit the release to the shoots. This difference in release of nutrients in shoots is probably caused by genotypic differences in absorption and movement of ions and this can be improved through breeding (Gerloff and Gabelman, 1983). The nutrient use efficiency, on the other hand, is the ability of the plant to produce maximum quantities of dry matter with minimal supply of plant nutrient elements (Swiader *et al*., 1994). The nutrient use efficiency can be improved through the efficient supply of plant nutrient elements in the soil, breeding and good agricultural practices at farm level (Gerloff, 1976).

## 2.12 Key Challenges Contributing to the Decreased Importance of Coffee as a Cash Crop

The key challenges contributing to the decreased importance of coffee as a cash crop include, low coffee productivity, under exploited quality potential, climate change and coffee cropping systems as explained below.

### 2.12.1 Low productivity and economic profitability of coffee farms

Tanzania's stagnated coffee production is largely the result of declining yields that resulted from the age of the coffee trees as well as inappropriate crop husbandry practices. It is usually considered that a coffee tree becomes economically unprofitable when it passes the age of 20-25 years (TCB, 2012). In Tanzania, most of the 240 million coffee trees around the country have exceeded this age (FAO, 2013). Their productivity has therefore been gradually declining over the years, largely causing the continuous decreasing yield at national level. This is generally exacerbated by poor farm management practices, including insufficient pruning and stumping of trees and poor management of pests and diseases, mainly CWD in Robusta coffee growing areas and CBD and CLR in Arabica coffee growing areas (TCB, 2012).

### 2.12.2 Under-exploited quality potential

It is estimated that about 90% of the coffee in Tanzania is currently home processed which results in inconsistent and heterogeneous quality because of poor post harvest practices, therefore, large international buyers currently tend to use Tanzania coffees in blends rather than developing Tanzania single origin coffee (Carr, 2003). The agronomic constraints such as low usage of inputs, poor crop husbandry practices like low additions of fertilizer and manure seem to reduce the proportion of sound heavy beans (Stiftung, 2004).

Regarding Robusta (Kagera area) the entirety of the production is currently sun-dried and quality is overall fairly good. There have been suggestions in the past to introduce washing stations to produce washed Robusta but the availability of enough water for washing the beans was limited and the price premiums that could be obtained were not yet clearly demonstrated (TCB, 2012).

### 2.12.3 The impact of climate change

Robusta coffee is also affected by climate extremes, though it can tolerate higher temperatures and is more resistant to some pests and diseases than Arabica coffee. This may be one reason why the percentage of global coffee production of Robusta has risen from 20 to 40% since 1980. Robusta does, however, require high rainfall, which, because of the increased likelihood of prolonged droughts, means that irrigation is likely to become an increasingly essential requirement (Coffee and climate, 2015). Coffee production is likely to move to higher altitudes due to the increase in temperature, which is an obvious feature of climate change (Haggar, 2011). Changes in the rainfall patterns are less clear due to the important differences between the models. It is likely that climate variability would increase in conjunction with the *Elnino/La Nina* cycles. This could generate an aggravation of extreme weather patterns (drought, floods, etc.) which could negatively impact the production of coffee (Haggar, 2011).

## 2.13 Coffee Cropping Systems and Their Effects on Coffee Yields

Throughout the country, coffee is produced under three main cropping systems, namely pure stand production (mainly in the south), intercropped coffee with bananas (mainly in the north and west) and estates sector (less than 10% of total production) (TCB, 2009).

The Northern zone which comprises Kilimanjaro, Arusha, Manyara and Tanga, grows some of the world's finest mild Arabica coffee. The production system is mixed between a majority of small holders (intercropping with bananas), and a few large estates located mainly in Arusha region (Mmari, 2012). The area under cultivation is estimated to reach 83 000 hectares with an average production of about 7 500 to 10 000 tons of parchment per annum. The cropping systems affect the yield per hectare (100-125 tonnes per hectare) of this area due to competitions from other crops grown as mixed for nutrients and water, especially when inter cropped with cereals (Mmari, 2012). The area of Kagera which covers 5 districts namely: Karagwe, Muleba, Bukoba, Misenyi and Biharamulo also practiced mixed farming where the coffee is mixed with food crops like bananas, yams, cassava and beans. The yields are always low with an average yield reaching about 500 kgs of clean coffee per hectare (TCB, 2012).

# CHAPTER THREE

## 3.0 MATERIALS AND METHODS

### 3.1 Description of the Study Site

The study was conducted in Bukoba Rural district, Kagera Region. This is a traditional coffee growing district, dominated by Robusta coffee. The District is located at an altitude of between 1200 m to 1300 m above sea level. Its coordinates are $1^{o}19'60''$ S and $31^{o}$ $30'0''$ E. On average, Bukoba rural district receives rainfall between 800 mm to 2,000 mm per annum and temperature between 20 °C to 30 °C (UNDP, 2014). The dominant parent rock in the area (Kagera region) from which the composite soil samples for the pot experiment were collected belongs to the Karagwe-Ankolean System (Maro, 2011). It consists of sequences of clay stones and fine-grained quartzitic sandstones with veins of quartz. The rocks are rich in ferromagnesian minerals and contain some mica (Maro, 2011). Some of the characteristics of study areas are as presented in Table 1.

### 3.2 Identification and Selection of the Study Sites

Soil sampling for the evaluation of the fertility status of the soils was carried out in some selected sites in eight villages of Bukoba rural district namely Igomba, Kiilima, Katangalala, Mishozi, Katale, Bugabo, Bulinda and Bugaruka. The soil sampling sites were randomly selected within each village based on the historical coffee production trends. Three landform types (hill top, gentle slope and plain) were the priority for taking soil samples as farmers tend to cultivate coffee on these landform types.

### 3.3 Soil Sampling

A total of eight composite soil samples were collected from each of the eight villages of Bukoba rural. In each village, 10 composite soil samples collected randomly through transect walk in areas with the similar crop history, physiographic features and textural classes. The surface litter and crop residues were scraped away and by using spade soil samples were taken at 10 sites in each uniform soil area at 0-40 cm depth mixed and constitute composite soil sample. The soil samples were sent to the TaCRI Lyamungo soil laboratory. The soils were then air-dried, ground using a soil grinder, sieved through the conventional 2-mm sieve and packaged in 1-litre plastic storage bottles for physical and chemical analysis.

**Table 1: Salient characteristics of the sites where soil samples collected**

| **Village** | **Coordinates** | | **Salient features** | | |
|---|---|---|---|---|---|
| | **Long°** | **Lat°** | **Textural class** | **Landscape characteristics** | **Crop history** |
| Igomba | 31.8086 | -1.2583 | Sandy loam | Gentle slope | Coffee, banana, beans, yams |
| Kiilima | 31.8240 | -1.2320 | Sandy loam | Gentle slope | Coffee, banana, vanilla |
| Katangalala | 31.8557 | -1.1938 | Sandy loam | Plain | Coffee, banana, potatoes |
| Mishozi | 31.8514 | -1.1459 | Sandy loam | Plain | Coffee, banana, yams |
| Katale | 31.8384 | -1.0838 | Sandy loam | Hill top | Coffee, banana, beans |
| Bugabo | 31.8340 | -1.0239 | Sandy loam | Hill top | Coffee, banana, vanilla |
| Bulinda | 31.7724 | -1.4267 | Sandy loam | Flat | Coffee, banana, vanilla |
| Bugaruka | 31.7942 | -1.4728 | Sandy loam | Flat | Coffee, banana, potatoes |

Key: Long°- Longitude Lat°- Latitude

### 3.4 Soil Analysis

The soil analyses undertaken included, particle size distribution, pH, exchangeable bases, cation exchange capacity, organic carbon, total nitrogen, and available phosphorus. Particle size distribution was determined by the hydrometer method (Gee and Bauder, 1986). Soil pH was determined in 1:2.5 soil water suspensions using pH-meter (Mclean, 1986). The cation exchange capacity was determined by distillation of $NH_4^+$ extracted with KCl in the residue soil after leaching of exchangeable bases (Chapman, 1965). Organic carbon was determined by the Walkley-Black wet-oxidation method (Nelson and Sommers, 1996). Total nitrogen was determined by the micro-Kjedahl method (Bremner, 1996). Available phosphorus was determined by the Bray 1 method (Bray and Kurtz, 1945).

### 3.5 Screen House Pot Experiment

The Pot experiment on the assessment of the response of the four coffee varieties to N, P and K was conducted at ARI Maruku, located at 1° 22' 33" South, 31° 48' 53" East, and an altitude of 1137 masl (Maplandia, 2005). The average annual temperature at Maruku is 20 °C and annual rainfall of 1806 mm (Maplandia, 2005). The warmest and coldest month of the year is March and July with an average temperature of 20.3 °C and 19.4 °C, respectively (Maplandia, 2005).

The bulk composite soil sample for the pot experiment was constituted of samples collected from only one village (Bugabo). The bulk composite soil sample from one (Bugabo village) out of 8 villages surveyed for soil fertility was collected at 0 to 40 cm of depth. The village was selected because of historical background of coffee diseases and low soil fertility. The bulk sample of the soil was taken to laboratory for chemical and physical analysis. The entire volume of soil was dried under shade and homogenized by removing stones and other major particles. Twenty-kilograms soil sample portions were weighed on a precision balance, and placed in 36 sealed plastic pots (15 L). Each pot was planted with one coffee seedling presenting specific Robusta variety i.e. MR 10, BK 27, 13/61 and ML 2. These Robusta coffee varieties used as test crops.

The pots were arranged in a 4x3 factorial scheme with three replications. The factors were 4 varieties of Robusta coffee (MR 10, ML 2, BK 27 and 13/61) and three rates of fertilizers (Urea, TSP and KCl) in a completely randomized design. The rates were: Urea (0, 150, 300 kg N/ha equivalent to 0, 75, 150 mg N/kg of soil), TSP (0, 75, 150 kg P/ha equivalent to 0, 37.5, 75 mg P/kg of soil) and KCl (0, 150, 300 kg K/ha equivalent to 0, 75, 150 mg K/kg of soil). The experimental unit consisted of a seedling of each genotype per pot. The coffee seedlings were provided by TaCRI and all of them were at least six month old. The fertilizer levels corresponding to each experimental plot were applied in the solid form, and divided into two applications. The first application was at the day of planting where three rates were applied (0 g Urea/pot, 0 g TSP/pot, 0 g KCl/pot; 1.62 g Urea/pot, 0.75 g TSP/pot, 1.25 g KCl/pot; and 3.25 g Urea/pot, 0.75 g TSP/pot, 2.5 g KCl/pot) which is equivalent to 0 mg N/kg of soil, 0 mg P/kg of soil, 0 mg K/kg of soil; 37.5 mg N/kg of soil, 18.75 mg P/kg of soil, 37.5 mg K/kg of soil; and 75 mg N/kg of soil, 37.5 mg P/kg of soil, and 75 mg K/kg of soil, respectively. The second application was at 120 days after planting where the remaining half of the Urea, TSP and KCl fertilizer rate was applied. The planted seedlings were continuously irrigated for the whole period (Six months) of the experiment to keep the soil moisture status at field capacity. Under field conditions, the N, P and K rates were: N (0, 150 and 300 kg/ ha), P (0, 75 and 150 kg/ ha) and K (0, 150 and 300 kg/ ha).

### 3.6 Plant Leaf Analysis and Calculation of the Efficiency Indices

After 180 days (6 months) of growth, the plants were uprooted, and the stem and branches, leaves and roots were separated by cutting the plant with sharp clean knife. The vegetative parts were removed, washed, weighed and dried separately in the shade. Each of these parts were separately packed in paper bags and dried in the oven, with forced air circulation at a temperature of 65°C to a constant weight to determine the dry matter of each plant part separated. The dry matter of roots (DMR), were determined by weighing the root materials separated from the aerial part of the plant on analytical balance. The mass of dry matter of the aerial part (DMAP) was obtained by the sum of the weight of the dry mass of leaves, stems and branches. The total dry matter (TDM) was obtained by the sum of the DMAP and the DMR.

The shoot and root dry samples were brought into solution form through digestion with acids that dissolve the solid plant parts and bring the plant nutrient in liquid form (wet digestion method) for estimation an analysis in the laboratory for total N, P and K contents as described by FAO (2008). The dry matter and the nutrient content in the vegetal tissues was used to calculate the following indices: (a) absorption/uptake efficiency (AE) = (total content of nutrient in the plant) /(root dry matter), according to Swiader *et al.* (1994); (b) translocation efficiency (TE) = [(content of the nutrient in the aerial part) /(total content of nutrient in the plant)] x 100, according to Li *et al.* (1991); and (c) utilization efficiency (UE) = (total dry matter produced) $^2$/(total content of nutrient in the plant), according to Siddiqi and Glass (1981).

### 3.7 Statistical Analysis

Nutrient absorption, translocation and use efficiency data were subjected to analysis of variance at ($p \leq 0.05$), using GENSTAT software 14th edition (2002) and the means were separated using Protected Fisher's Least Significant difference (LSD) test at 5% probability.

# CHAPTER FOUR

## 4.0 RESULTS AND DISCUSSIONS

### 4.1 Soil Fertility Status of the Selected Coffee Growing Areas of Bukoba Rural District

Some of the physical and chemical properties of the soils from the selected villages are as presented in Table 2.

### 4.1.1 Soil pH

The pH of the soils from the selected sites ranged from 4.12 to 5.53. The soil pH of all the soils is rated as low (<5.50) according to Landon (1991). The soil reaction ranged between extremely acidic (pH <4.6) to very strongly acidic (4.6 to 5.5) according to ratings by Motsara and Roy (2008). The coffee growing areas with extreme acid soils was Bugabo, while the areas with strong acid soils were from Bugaruka, Kiilima, Katangalala, Mishozi, Bulinda, Igomba and Katale (Table 2).

The probable causes of the extreme to very strongly acid soil reactions of the soils could be extensive weathering of the soils and high precipitation, which led to leaching of the bases. It is also possible that the acidic nature of the parent materials from which the soils are formed contributed to acidic soils in this area. The dominant parent material in the area belongs to the Karagwe-Ankolean System which consists of sequences of claystones and fine-grained quartzitic sandstones with veins of quartz (Maro, 2012). The rocks are rich in ferromagnesian minerals and contain some mica (Maro, 2012). Further incorporation of plant residues with residual acid effects could account for the low soil pH.

**Table 2: Some chemical and physical properties of the soils from the selected villages, Bukoba Rural District**

| **Parameters** | **Villages** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **BK1** | **BK2** | **BK3** | **BK4** | **BK5** | **BK6** | **BK7** | **BK8** |
| pH($H_2O$) | 5.31 | 4.7 | 4.72 | 4.55 | 5.53 | 4.12 | 4.79 | 4.58 |
| Total N (%) | 0.17 | 0.06 | 0.14 | 0.11 | 0.08 | 0.09 | 0.19 | 0.08 |
| Organic carbon (%) | 0.44 | 0.09 | 2.1 | 1.43 | 0.79 | 0.4 | 2.25 | 1.1 |
| Organic matter (%) | 0.75 | 0.16 | 3.61 | 2.453 | 1.36 | 0.69 | 3.87 | 1.89 |
| Extractable P (mg/kg) | 41.2 | 33.22 | 30.22 | 35.42 | 40.24 | 68.29 | 20.21 | 20.98 |
| Exchangeable K (cmol/kg) | 1.34 | 1.54 | 0.33 | 0.34 | 0.17 | 1.67 | 0.11 | 0.58 |
| Exchangeable Ca (cmol/kg) | 3.39 | 2.26 | 4.35 | 1.48 | 4.24 | 4.22 | 1.58 | 1.62 |
| Exchangeable Mg (cmol/kg) | 1.45 | 1.56 | 1.39 | 1.26 | 1.51 | 1.24 | 1.55 | 1.65 |
| Exchangeable Na (cmol/kg) | 0.53 | 0.09 | 0.13 | 0.31 | 0.57 | 0.12 | 0.07 | 0.23 |
| CEC (cmol/kg) | 40 | 25 | 28 | 22 | 37 | 24 | 23 | 28 |
| PBS | 16.77 | 21.82 | 22.14 | 15.39 | 17.54 | 30.19 | 14.39 | 14.58 |
| **Particle size distribution** | | | | | | | | |
| (i) Sand (%) | 60 | 60 | 70 | 60 | 60 | 60 | 60 | 70 |
| (ii) Silt (%) | 20 | 30 | 10 | 30 | 10 | 30 | 30 | 20 |
| (iii) Clay (%) | 20 | 10 | 20 | 10 | 30 | 10 | 10 | 10 |
| **Textural class** | SL | SL | SL | SL | SL | SL | SL | SL |

BK1-Igomba, BK2-Kiilima, BK3-Katangalala, BK4-Mishozi, BK5-Katale, BK6-Bugabo, BK7-Bulinda, BK8-Bugaruka

Sys *et al.* (1993) noted that Robusta coffee thrives well in the soil pH range of 4.5 – 7.0 with the optimum range of 5.3 – 6.0. So the pH range of the soils in selected sites of the coffee growing villages (BK 2, BK 3, BK 4, BK 6, BK 7 and BK 8) were not within the optimum range for Robusta coffee production. Two sites namely BK 1 and BK 5 soil pH were within the optimum range suitable for coffee production. For the sites where the range was below the optimum level, liming with mineral dolomite ($Ca.Mg(CO_3)_2$) is essential to optimize coffee production (Horneck, 2011). Also application of organic manures and neutral and alkaline fertilizers would help to stabilize the soil pH within the optimum range for Robusta coffee and improve the fertility status of the soil as well.

The soil reactions have different implications to the quality of coffee and the availability of other nutrient elements. Acidic conditions enhance the presence of Aluminium trivalent cation ($Al^{3+}$) (Lidon and Barreiro, 2002), which is the most toxic of all Al species available to plants (Hoshino *et al*., 2000). The $Al^{3+}$ cause toxicity in roots which changes the cation availability and reduced root growth (Mora *et al*., 2006). Under acidic conditions some of the vital nutrients such as P, Ca and Mg are transformed into forms not available to plants. Acid conditions also cause basic cations loss due to heavy leaching from the soil with low CEC. At low pH, Al-toxicity is reported as the main stress factor for plant growth and development (Poschenrieder *et al*., 2008).

### 4.1.2 Total Nitrogen

The total nitrogen of the soils from the selected sites ranged from 0.056 to 0.192 % (Table 2). The total nitrogen of all the soils are rated as low (0.10 to 0.20) according to the rating by Landon (1991). The soil total nitrogen values obtained, ranged from very low (<0.10) to low (0.10 to 0.20). Areas with very low soil nitrogen were Kiilima, Katale, Bugabo and Bugaruka while the areas with low soil nitrogen were Igomba, Katangalala, Mishozi and Bulinda.

The probable causes of the low nitrogen in the soils could be due to low soil organic matter in the soil and losses of N through soil erosion, and leaching and uptake by plants without replenishment. Addition of manures and compost is one of the good agronomic practices which could improve soil nitrogen. Further incorporation of the coffee plant residues (leaves) could also increase the total nitrogen in the soils (i.e. N contained in the falling leaves) and application of the appropriate nitrogen fertilizers. An adequate nitrogen supply would promote rapid plant development, specifically through the increase in the number of leaf pairs and plagiotropic branches per plant, number of nodes per branch, and number of fruiting nodes and flowers per node (Malavolta, 1986). These coffee plant growth parameters and variables are associated with higher coffee yields and quality (Willson, 1985; Malavolta, 1986; Fahl *et al*., 1994, Nazareno *et al*., 2003). Low nitrogen in the soil may results to stunted growth of the plants and this will cause reduction of yield per season. Use of well prepared manure, compost and industrial fertilizers like CAN and NPK can improve the level of nitrogen in the soil.

### 4.1.3 Organic carbon

The % organic carbon contents of the soils studied ranged from 0.09% to 2.25% (Table 2). The soil organic carbon at the selected sites in the coffee growing villages is rated as very low (<0.6) to medium (1.26 to 2.50) according to the rating by Landon (1991). This condition is probably caused by low application of organic manure by farmers, little or no mulching and mixing of many non leguminous crops in the same field without returning back the crop residues to the soils after harvesting. Coffee flourishes well in soils with OC ≥ 1.5% (Sys *et al*., 1993). Most of the sites studied (BK 7, BK 3, BK 4, BK 8, BK 2 and BK 5) have optimum soil organic carbon for coffee production and few have below the optimum level. For those sites (BK1, BK2 and BK6) with low organic carbon to correct such a problem organic soil amendments like manure and compost applications are needed.

The ratios of carbon to nitrogen of the experimental soils ranged from 1.607 to 15 (Table 2) and this indicates the quality of organic matter range from moderate (if C: N ranges from 14-20) to good quality (if C: N ranges from 8-13) according to rating by Landon (1991) and this indicate that the soil organic matter is easily decomposable. Low organic carbon means low organic matter and hence the negative implications in the physical, chemical and biological properties of the soils, such as soil structure, water retention, nutrient content and retention and microbiological activities in the soil.

### 4.1.4 Available phosphorus

The available phosphorus of the soils from the sites studied ranged from 20.21 to 68.29 mg kg$^{-1}$ and followed the trend BK 7< BK 8< BK 3< BK 2< BK 4< BK 5< BK 1<BK 6 (Table 2). According to the rating by Landon (1991), the available P of the soils from the study areas has sufficient phosphorus (> 15 mg P/kg) for crop production. A study conducted by Sønsteby et al. (2004) established increased amounts of phosphorus and potassium levels in crop leaves in plots mulched with wood chips. Phosphorus availability to plants is strongly influenced by soil pH and usually maximized when the pH is between 5.5 and 7.5 (Kebeney, 2015). Phosphorus applications generally are not recommended when soil test P is greater than 15 mg/kg. However, due to soil reaction (acidic nature) P fixation is expected and this could be detrimental to coffee production without P fertilization. Liming could correct the pH of the soil and enhance easy uptake of P from the soil by coffee tree.

### 4.1.5 Exchangeable potassium

The exchangeable K of the composite soil samples from the sites studied ranged from 0.11 to 1.81 cmol (+) kg$^{-1}$ and followed the trend BK 7< BK 5< BK 3< BK 4< BK 8< BK 1< BK 2< BK 6 (Table 2). The soil K of the study sites is rated as low (< 0.2 cmol(+)/kg) to high (> 0.4 cmol(+)/kg) according to the rating by Landon (1991). Out of eight soils, two soils (BK7 and BK5) had low exchangeable K and two soils (BK3 and BK4) had medium exchangeable K, while the rest of the soils had sufficient K (Table 2).

The probable causes of low K in the soils could be little applications of K fertilizers and low contents K in the parent materials of the soils. Under acidic conditions there is presence of highly weathered clay which causes aluminum toxicities which may cause poor root development, which hinders potassium uptake. When acidic soils are limed, exchangeable K increases due to increases in the cation exchange capacity (Maro, 2012). Potassium enhances general growth of plants, efficient water utilization, floral initiation and fruit setting. Potassium has a big impact on coffee yields and quality, especially berry size. Coffee removes as much of potassium per ton of yield as nitrogen indicating the high demand and luxurious uptake of K by the coffee plants (Maro, 2012).

### 4.1.6 Exchangeable calcium

The exchangeable calcium of the composite soil sample from the experimental sites ranged from 1.475 to 4.235 cmol (+) kg$^{-1}$ and followed the trend BK 4< BK 7< BK 8< BK 2< BK 1< BK 5< BK 3< BK 6 (Table 2). The soil Ca of the experimental sites would be rating as low to high (0.5-6.0) according to the rating by Landon (1991). Low calcium is probably caused by low soil pH which enhances leaching of bases coupled with the high natural precipitation at the experimental sites. Altitude also is another factor for variations of the exchangeable calcium. Change of altitude height caused significant differences for solar radiation amount, effective accumulated temperature, temperature difference, air humidity, etc (Jian *et al*., 2005). A study conducted by Shao *et al.* (2011) showed that Altitude was an important factor affecting the soil fertility, and the status of exchangeable calcium content at different altitude (< 800 m – 69.30 to 1516.53 mg/kg, 800 to 1000 m – 1500 to 2870.50 mg/kg and > 1000 m – 1889.17 to 2916.78 mg/ kg).

### 4.1.7 Exchangeable magnesium

The exchangeable magnesium of the composite soil samples of the selected sites ranged from 1.24 to 1.65 cmol (+) kg$^{-1}$ and followed the trend BK 6< BK 4< BK 3< BK 1< BK 5< BK 7< BK 2<BK 8 (Table 2). The soil exchangeable Mg of the selected sites would be rated as medium (0.75-2.0) according to the rating by Landon (1991). The Mg level of the study areas soils are optimum for coffee production, however continual leaching of this

element may lead to its deficiency. Magnesium deficiencies on acidic soils can be corrected by liming with dolomite (calcium-magnesium carbonate [$CaCO_3$-$MgCO_3$].

### 4.1.8 Exchangeable sodium

The exchangeable sodium of the composite soil samples of the selected sites ranged from 0.07 to 0.57 cmol (+) kg$^{-1}$ and followed the trend BK 7< BK 2< BK 6< BK 3< BK 8< BK 4< BK 1< BK 5 (Table 2). The soil exchangeable Na is rated as low (0.10-0.30) according to the rating by Landon (1991). Sodium is not an essential plant nutrient but a beneficial element for the growth of plants. High levels of sodium are detrimental to soil structure, soil permeability and plant growth (Horneck, 2011). The ESP values for the experimental sites range from 0.15 to 1.5% (Table 2) an indication that the soils are neither sodic, saline nor saline sodic, hence not limiting with respect to coffee production.

### 4.1.9 Cation exchange capacity

The cation exchange capacities of the soils of the selected sites ranged from 22 to 40 cmol (+) kg$^{-1}$ and followed the trend BK 4< BK 8< BK 7< BK 4, BK 6< BK 1< BK 3< BK 2 (Table 1). The CEC of the experimental sites is rated as medium (12.1-25.0) to high (25.0-40.0) according to the rating by Landon (1991). Organic materials in soil increase the CEC through an increase in available negative charges, as such, organic matter build-up in soil usually improves the fertility status of the soil (Horneck, 2011).

## 4.2 Pot Experiment

### 4.2.1 Response of four Robusta coffee varieties to N, P and K application

The response of the four Robusta coffee varieties, namely MR 10, ML 2, BK 27 and 13/61 in terms of dry matter yield, nutrient concentrations, uptake efficiency, translocation efficiency and use efficiency to N, P and K applied to the pot experiment are as presented in Tables 3 to 6 and appendices 1 to 13.

#### 4.2.1.1 Effect of applied N, P and K on the total dry matter yield of the four Robusta coffee varieties

The effects of applied N, P and K from Urea, TSP and KCl respectively in terms of total dry matter yield for the four Robusta coffee varieties are as presented in Fig. 1. and Appendix 1. The total dry matter yields of the three Robusta coffee varieties (13/61, MR 10 and ML 2) increased with increasing rates of applied fertilizers but under higher rates (150 g/pot) the dry matter yield decreased. For the variety BK 27 the dry matter yield decreased as the rates of N, P and K fertilizers increased. The mean total dry matter yield at different rates of N, P and K fertilizers followed the trend 13/61> ML 2> MR 10> BK 27. The differences in dry matter yield were statistically significant within the varieties and between the varieties. The probable cause for the differences in dry matter yield between the varieties on the different rates of N applied could be the differences in root structure of a particular variety and the leaf and branch architecture. From the study, a coffee variety with long and robust root hairs seems to be more effective on absorption of the added nutrients and hence good dry matter yield.

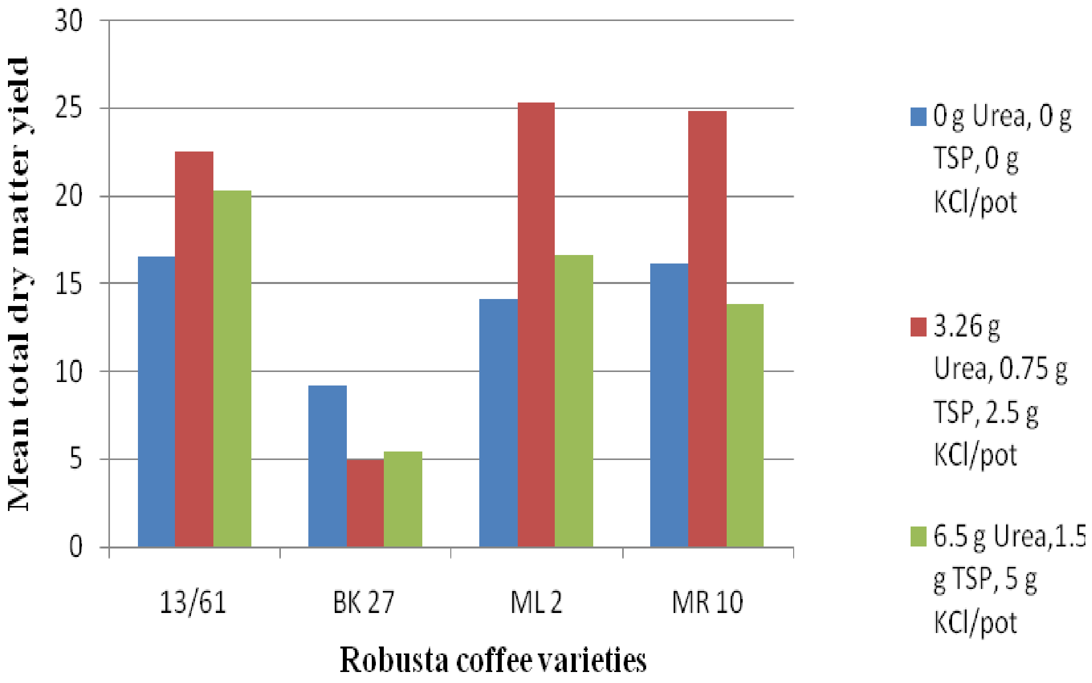

**Figure 1: Total dry matter yield of the four Robusta coffee varieties subjected to three doses of N, P and K from Urea, TSP and KCl fertilizer**

#### 4.2.1.2 Effect of applied Fertilizers (Urea, TSP and KCl) on the N, P and K contents on the four Robusta coffee varieties

The effect of applied Urea, TSP and KCl on the nutrient contents (N, P and K) in the four varieties of Robusta coffee is presented in Table 3 below and Appendices 2, 3 and 4:

**Table 3: Total N, P and K content of the four varieties of Robusta coffee subjected to three levels of N, P and K**

| **Nutrients Rate (mg/kg)** | **Varieties** | **Total N content %** | **Total P content %** | **Total K content %** |
|---|---|---|---|---|
| $N_0P_0K_0$ | 13/61 | 3.50a | 0.152aa | 1.762a |
| | MR 10 | 4.667abc | 0.121aa | 2.512ab |
| | BK 27 | 3.710ab | 0.155aa | 2.520ab |
| | ML 2 | 3.850ab | 0.111aa | 2.345ab |
| $N_{75}P_{37.5}K_{75}$ | BK 27 | 5.028bcd | 0.298ab | 3.184bc |
| | 13/61 | 6.370de | 0.406bb | 3.059bc |
| | MR 10 | 6.580e | 6.58ba | 3.142bc |
| | ML 2 | 7.058e | 0.309ab | 3.053bc |
| $N_{150}P_{75}K_{150}$ | BK 27 | 5.740cde | 0.468cc | 3.183bc |
| | MR 10 | 5.787cde | 0.304ac | 2.935bc |
| | 13/61 | 6.848e | 0.567abC | 3.583c |
| | ML 2 | 7.035e | 0.364bc | 3.669c |
| CV (%) | | 14.7 | 21.2 | 17.7 |

Means followed by the same letter vertically do not differ among themselves by Fisher's protected significant test at 5% of probability

The effects of applied N as Urea (46 % N) on total N contents (in the whole coffee plant) in the four Robusta coffee varieties are presented in Table 3. and Appendix 2 The N contents in the four Robusta coffee varieties increased with increasing rates of applied N and the increase were in the order ML 2> MR 10> 13/61> BK 27 based on the % N content. The increase in total N with increasing N rates was statistically significant within varieties and between varieties. The N content was rated as high (2.30-3.00%) according to the rating by Ctahr (1994). The high concentration of nitrogen in coffee plants is due to the coffee material used. The seedlings used were from the coffee cuttings, which obtained from the mother garden of already established coffee tree. The increase in N contents with increasing rates of N applied to the soil could be attributed to low N contents in the soil. The application of N as Urea increased the N content and availability from the soil, hence the positive response. Similar results have been reported by Tomaz *et* *al*. (2004) when assessing the efficiency of grafted conilon coffee for N, P and K and observed that there was increase in % total N contents as the rate of N applied increased. The probable causes of the differences in nitrogen concentration in each variety could be due to differential behaviour between the species or cultivars of the same species in nitrogen uptake and utilization. Furlani *et al*. (1986), who evaluated the differential behaviour of rice breeding lines in nitrogen uptake and utilization from nutritive solution, verified that the differentiation among plants was, mainly, due to the N use capacity, with variation in the total dry matter. MR 10 variety showed to contain large N contents (Table 3) in a limited soil N and this indicate the efficiency of this variety in low soil nitrogen condition. The observations above could be a useful tool for characterizing the best genotype, which can adapt to low soil nitrogen.

The effect of applied P as TSP (46% $P_2O_5$) on P contents in the four Robusta coffee varieties are as presented in Table 3 and Appendix 3. The P contents in the four Robusta coffee varieties increased with increasing rates of applied P and were in the order 13/61> BK 27> ML 2> MR 10. The increase in total P with increasing P rates was not statistically significant between the varieties, but they were statistically significant within the varieties. The % P content were rated as high (0.12-0.20%) according to the rating by Ctahr (1994). The acidic nature of the soils which hinders the uptake of P by the varieties could be the reasons for none statistically differences in P concentrations. A study by Lima *et al.* (2013) presented the different results for *Conilon coffee* where P contents in conilon coffee clones increased as the phosphorus level increased. These differences between genotypes of the same species can be caused by the root system morphology, the ratio between root and shoot and the root's distribution, architecture and diameter (Amaral *et al.,* 2012). When characterizing the efficiency of each variety for P content in the lower P supply in the soil, variety BK 27 showed to be efficient with the highest mean value (Table 3).

The effect of applied K as KCl (60% $K_2O$) on K contents in the four Robusta coffee varieties are presented in Table 3 and Appendix 4. The K contents in the four Robusta coffee varieties increased with increasing rates of applied K and the potassium contents were in the order ML 2> BK 27> MR 10> 13/61 based on the K contents. The increases in K content with increasing K rates were not statistically significant between the varieties and within the varieties, and this could be due to the nature of the varieties. All the four varieties have good canopy and root systems. The % K content was rated as high (2.00-2.50%) according to the rating by Ctahr (1994). The insignificant increase in % K with increasing rates of K applied to the soil could be attributed to the applied K as KCl fertilizer. A similar study conducted by Fahl *et al*. (1998) on the *Coffea arabica* cultivars grafted onto *Coffea canephora* progenies reported significant differences in K contents as the rates of K applied were increased. According Tiffney and Niklas (1985), this different behaviour between genotypes of the same species is associated with better adaptation to adverse conditions, and also with the distinct ability that they have to change the geometrical configuration of the root system to exploit the resources in a more efficient way.

#### 4.2.1.3 Effect of applied N, P and K (Urea, TSP and KCl) on the nitrogen, phosphorus and potassium absorption efficiency in the four Robusta coffee varieties

The effect of applied Urea (46 % N), TSP (46 % $P_2O_5$) and KCl (60 % $K_2O$) on the nitrogen, phosphorus and potassium absorption efficiencies by the four Robusta coffee varieties are as presented in the Table 4 and Appendices 5, 6 and 7 respectively.

**Table 4: NAE, PAE and KAE of four Robusta coffee varieties subjected to three levels of N, P and K**

| NPK Rate (mg/kg) | Varieties | NAE (mg g-1) | PAE mg g-1 | KAE mg g-1 |
|---|---|---|---|---|
| $N_0P_0K_0$ | 13/61 | 0.690a | 1.560 | 0.387a |
| | MR 10 | 1.100a | 1.347 | 0.590a |
| | BK 27 | 1.400a | 1.483 | 0.953a |
| | ML 2 | 0.957a | 1.330 | 0.557a |
| $N_{75}P_{37.5}K_{75}$ | BK 27 | 9.320b | 2.083 | 6.043c |
| | 13/61 | 1.170a | 2.177 | 0.563a |
| | MR 10 | 1.773a | 1.983 | 0.883a |
| | ML 2 | 1.323a | 2.033 | 0.583a |
| $N_{150}P_{75}K_{150}$ | BK 27 | 7.173b | 2.850 | 3.850b |
| | MR 10 | 1.890a | 2.283 | 0.927a |
| | 13/61 | 1.433a | 2.190 | 0.760a |
| | ML 2 | 1.890a | 2.007 | 0.933a |
| $LSD_{0.05}$ | | 1.865 | 0.2123 | 1.164 |

Means followed by the same letter vertical do not differ among themselves by Fisher's protected significant test at 5% of probability

The effect of applied N as Urea (46 % N) on nitrogen uptake efficiency by the four Robusta coffee varieties are as presented in Table 4 and Appendix 5. The nitrogen uptake efficiency in the four Robusta coffee varieties increased with increasing rates of applied N and the NAE were in the order BK 27> MR 10> ML 2> 13/61 (Table 4). Under control treatment there was no significant difference in NAE for the four varieties. When the rate of Urea increased only one variety (BK 27) differ significantly with the rest of the varieties (Table 4). When the rate increased again variety BK 27 differs significantly in the absorption of nitrogen with the rest (Table 4). There was an increase in NAE with increasing N rates, although not statistically significant between the varieties and within the varieties. The increase of NAE with increasing rates of N applied to the soil could be attributed to the ability of a plant to capture nitrogen from the soil which depends on soil type, environment and species. A study conducted by Lima *et al*. (2003) in Robusta coffee for absorption efficiency of N revealed that the absorption efficiency of nitrogen of genotypes increased with the supply of nitrogen in the soil. Speaking of the best genotype in the limited supply of nutrient elements, BK 27 variety observed to perform best under low N supply by having high value of NAE although the difference was not statistically different followed by MR 10 (Table 4 and Appendix 5). It has been estimated that 50–70 % of the nitrogen provided to the soil is lost and therefore, improving NUE is essential in order to reduce damage due to nitrate leaching, ecosystem saturation and water pollution (Hodge, 2000).

The effects of applied P in terms of phosphorus uptake efficiency by the four Robusta coffee varieties are as presented in Table 4 and Appendix 6. The phosphorus uptake efficiency in the four Robusta coffee varieties increased with increasing rates of applied P and the PAE were in the order BK 27> 13/61> MR 10> ML 2 but the increases were not statistically significant (Table 5). The increases in PAE with increasing P rates were not statistically significant between the varieties and within the varieties. The increase of PAE with increasing rates of P applied to the soil, could be attributed to the adequate structure and distribution of the root system, chemical changes in the rhizosphere and exudation of substances capable of solubilizing nutrients, presence of mycorrhizae, and tolerance to conditions of low pH or high levels of exchangeable aluminum (Fonseca *et al*., 2004). Studies conducted by Fonseca *et al*., about nutritional efficiency in clones of conilon coffee for phosphorus and revealed differences among varieties in the absorption of phosphorus. In his study he showed certain varieties like CV-04 (7.25), CV-10 (4.80), CV-11 (13.15) and CV-12 (10.82) had high capacities to absorb P than the other varieties. Under low supply of P variety 13/61 had higher mean value of PAE than the rest and this indicate the potential of this variety in soils with low available P.

The effects of applied K on potassium uptake efficiency by the four Robusta coffee varieties are as presented in Table 4 and Appendix 7. The potassium uptake efficiency in the four Robusta coffee varieties increased with increasing rates of applied K and the KAE were in the order BK 27> ML 2> MR 10> 13/61 (Table 6). There were no statistical significant of KAE when no K was applied between varieties. However there were significant differences when the rates of K as KCl increased to 15 g/pot (equivalent to 750 mg K/kg) for variety BK 27 (Table 4). Other varieties differs themselves in KAE but not statistically. The increases in KAE with increasing K rates were statistically significant between the varieties and within the varieties. The increase of KAE with increasing rates of K applied to the soil could be attributed to the sufficient supply of K by the application of the K fertilizer to the soil which increases the availability of K in the soil. A study conducted by Tomaz *et al*. (2004) on the comparison of nutritional efficiency among hydroponic grafted young coffee trees for K presented similar results for increase of K uptake as K supply increased. Efficiency on absorbing potassium observed to be high for BK 27 variety under low rate of fertilizer and this shows the ability of the variety to perform under poor soil nutrient conditions.

#### 4.2.1.6 Effect of applied N, P and K on nitrogen, phosphorus and potassium translocation efficiency by the coffee plants

The effect of applied Urea (46 % N), TSP (46 % $P_2O_5$) and KCl (60 % $K_20$) on the nitrogen translocation efficiency (NTE), phosphorus translocation efficiency (PTE) and potassium translocation efficiency (KTE) by the four Robusta coffee varieties are presented in the Table 5 and Appendices 8, 9 and 10.

**Table 5: NTE, PTE and KTE of four Robusta coffee varieties subjected to three levels of N, P and K**

| NPK Rate (mg/kg) | Varieties | NTE (%) | PTE (%) | KTE (%) |
|---|---|---|---|---|
| $N_0P_0K_0$ | **BK 27** | 49.4 a | 31.28a | 38.80a |
| | **ML 2** | 51.00ab | 24.65a | 46.41abc |
| | **MR 10** | 51.98ab | 25.92a | 42.16ab |
| | **13/61** | 57.97 b | 34.58a | 49.42abc |
| $N_{75}P_{37.5}K_{75}$ | **MR 10** | 51.22ab | 49.35b | 55.82bc |
| | **ML 2** | 53.45ab | 48.83b | 38.53a |
| | **13/61** | 55.98ab | 49.23b | 52.33abc |
| | **BK 27** | 56.38ab | 48.61b | 52.23abc |
| $N_{150}P_{75}K_{150}$ | **BK 27** | 48.99a | 45.68b | 61.06c |
| | **MR 10** | 51.58ab | 50.25b | 53.11abc |
| | **13/61** | 52.04ab | 50.56b | 49.42abc |
| | **ML 2** | 55.28ab | 55.11b | 37.67a |
| $LSD_{0.05}$ | | 4.411 | 5.787 | 8.98 |

Means followed by the same letter vertical do not differ among themselves by Fisher's protected significant test at 5% of probability

The effect of applied N as Urea (46 % N) on nitrogen translocation efficiency in the four Robusta coffee varieties are as presented in Table 5 and Appendix 8. When there is no fertilizer varieties differ in the nitrogen translocation efficiency significantly. When the rate of fertilizer increased there was no significant difference between varieties in NTE. Nitrogen translocation efficiency in the two Robusta coffee varieties (ML 2 and BK 27) increased with increasing rates of applied N and for the two varieties (MR 10 and 13/61) decreased with increasing the rate. However the mean for NTE were in the order 13/61> ML 2> BK 27> MR 10 (Table 5). The increase in NTE with increasing N rates (for ML 2 and BK 27) were statistically significant between the varieties and within the varieties while the decreases in NAE with increasing N rates (for MR 10 and 13/61) were statistically significant between the varieties and non statistically significant within the varieties. Differences between genotypes on translocation of nitrogen can probably be caused by differences between varieties with respect to vascular anatomy and growth habit. Several studies in other crops showed the differential behavior between the species or cultivars of the same species in nitrogen uptake and utilization (Fageria and Barbosa Filho, 1982; Wuest and Cassman, 1992).

The effect of applied P as TSP (46 % $P_2O_5$) on phosphorus translocation efficiency in the four Robusta coffee varieties are as presented in Table 5 and Appendix 9. The phosphorus translocation efficiencies by the four Robusta coffee varieties increased with increasing rates of applied P and the PTE were in the order 13/61> MR 10> BK 27> ML 2 (Table 8). The increases in PTE with increasing P rates were statistically significant between the varieties and within the varieties. The increase of PTE with increasing rates of P applied to the soil could be attributed to genotypic differences in phosphorus absorption and movement which determine the movement of ions through the roots and their release into the xylem in several steps that limit the release to the shoots (Lima, 2015). Similar results have been reported by Tomaz *et al.* (2004) whereby increasing the rates of P increased the P translocation efficiency of the variety. Under low P supply, 13/61 variety had higher mean value than the rest and this means that the variety is efficient in low soil P.

The effect of applied K as KCl (60 % $K_20$) on potassium translocation efficiency in the four Robusta coffee varieties are as presented in Table 5 and Appendix 10. The potassium translocation efficiency in the two Robusta coffee varieties (MR 10 and BK 27) increased with increasing rates of applied K while the other two varieties (ML 2 and 1361) the efficiency decreased as the rates of K increased. The mean KTE were in the order 13/61> BK7> MR 10> ML 2 (Table 5). The increases in KTE with increasing K rates were statistically significant between the varieties and within the varieties. The increases of KTE with increasing rates of K applied to the soil, could be attributed to genotypic differences in phosphorus absorption and movement and also the placement of K to the soil as KCl fertilizer which increase the availability of K. Variety 13/61 was highly efficient on translocation of potassium under low rate of fertilizer and this indicates the ability of this variety under low fertility soils.

#### 4.2.1.9 Effect of applied Fertilizers (Urea, TSP and KCl) on nitrogen, phosphorus and potassium use efficiency by the coffee plants

The effect of applied Urea (46 % N), TSP (46 % $P_2O_5$) and KCl (60 % $K_2O$) on the nitrogen, phosphorus and potassium translocation efficiencies in the four Robusta coffee varieties is presented in the Table 6 and Appendices 11, 12 and 13.

**Table 6: NUE, PUE and KUE of four Robusta coffee varieties subjected to three levels of N, P and K**

| NPK rate (mg/kg) | Varieties | NUE (g2 mg-1) | PUE (g2 mg-1) | KUE (g2 mg-1) |
|---|---|---|---|---|
| $N_0P_0K_0$ | BK 27 | 23.21ab | 449a | 34.5ab |
| | MR 10 | 56.67abc | 2395ab | 105.2abc |
| | ML 2 | 61.92abc | 1318 a | 93.3abc |
| | 13/61 | 86.98bc | 2184a | 197.2abc |
| $N_{75}P_{37.5}K_{75}$ | BK 27 | 5.11a | 586a | 8.0a |
| | 13/61 | 81.94abc | 1799a | 169.9abc |
| | ML 2 | 92.40bc | 1825a | 220.7bc |
| | MR 10 | 119.74c | 5459c | 273.9c |
| $N_{150}P_{75}K_{150}$ | BK 27 | 5.26a | 397a | 9.4a |
| | MR 10 | 34.54ab | 4863bc | 67.8ab |
| | ML 2 | 44.63abc | 2822abc | 77.6ab |
| | 13/61 | 62.02abc | 2184 a | 127.0abc |
| $LSD_{0.05}$ | | 46.98 | 1540.1 | 109.6 |

Means followed by the same letter vertical do not differ among themselves by Fisher's protected significant test at 5% of probability

The effect of applied N on the nitrogen use efficiency in the four Robusta coffee varieties are as presented in Table 6 and Appendix 11. The nitrogen use efficiency in the two Robusta coffee varieties (MR 10 and ML 2) but the efficiency decreased under high rates of N applied. For the other two varieties (BK 27 and 13/61) the efficiency decreased with increasing rates of N applied. The NUE means followed the trend 13/61> MR 10> ML 2> BK 27 (Table 6). The increase in NUE with increasing N rates for varieties MR 10 and ML 2 was statistically significant between the varieties and within the varieties. Generally it was observed that the nitrogen use efficiency depend on the genetic variability of the coffee varieties (Iannini, 1984). Several studies for other crops show the differential behavior between the species or cultivars of the same species in nitrogen uptake and utilization (Iannini, 1984). To improve N efficiency in crop production, integrated N management strategies that take into consideration improved fertilizer along with soil and crop management practices are necessary. Including livestock production with cropping offers one of the best opportunities to improve NUE (Fageria, 2005).

The effect of applied P on the phosphorus use efficiency in the four Robusta coffee varieties are as presented in Table 6 and Appendix 12. The phosphorus use efficiency in the four Robusta coffee varieties increased with increasing rates of applied P. The means for PUE followed the trend MR 10> 13/61> ML 2>BK 27 (Table 6). The increases in PUE with increasing P rates for the four varieties were statistically significant between the varieties and within the varieties. The increases of the PUE might be due to the greater metabolic efficiency of these varieties. A study conducted by Amaral (2012) on conilon coffee noted that conilon coffee clones present different responses in terms of dry matter production in each level of phosphate fertilization. The P use efficiency from the soil and fertilizers could be improved through modifying surface soil properties (texture, structure, water infiltration and aeration), managing surface soil and P content, and P sources and optimizing P use through the use of economically appropriate rates and timing (FAO, 2007).

The effect of applied K on potassium use efficiency in the four Robusta coffee varieties are as presented in Table 6 and Appendix 13. The potassium use efficiency in the two Robusta coffee varieties (MR 10 and ML 2) increased with increasing rates of applied K but decrease under higher rates of K applied. The KUE for the other two varieties (BK 27 and 13/61) decreased with increasing rates of K applied. The means for KUE followed the trend 13/61> MR 10> ML 2> BK 27 (Table 6). The increase or decrease in KUE with increasing K rates for the four varieties was statistically significant between the varieties and within the varieties. The increase or decrease of the KUE might be due to nutritional requirement being variable between genotypes of the same species, depending on the genetic and phenotypic variability (Fageria, 2005). The study conducted by Martin *et al.* in conilon coffee also revealed the differential K use efficiency within the genotypes. Under low K in the soil the variety 13/61 observed to be efficient on the use of absorbed nutrient element for dry matter yield and this indicate the potential of the variety under low K soils.

# CHAPTER FIVE

## 5.0 CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Conclusions

The evaluation of the fertility status of the soils was conducted in 8 villages of Bukoba rural district with interpretation based on the requirements for coffee crop production. All parameters of soil fertility are fully explained and documented, including how they affect the decisions in the field. The functions of various nutrients in the plants were outlined. Then the analytical results were given and interpreted, with immediate soil management recommendations given. For the characterization of the best varieties, various nutrient use efficiency indices calculated and documented and the varieties grouped either as effective and responsive or non effective and responsive based on their efficiencies on absorption, translocation and use of N, P and K. Overall, there is consent in relation to the concept of nutritional efficiency to characterize coffee varieties in their ability to absorb and utilize plant nutrients.

### 5.2 Recommendations

From the results of this research work, the following recommendations can be made:

1. On the improvement of the fertility status of the soil
    - i. Evaluation of the fertility status of coffee soils should be part and parcel before any fertilizer recommendations.
    - ii. Fertilizer recommendations should inclusively deal with individual coffee variety not only for the yield parameters, but also their response and efficiency with the use, absorption and translocation of the added plant nutrients.

2. On the best rates of N, P and K for better response of the varieties
    i. During young stages of the coffee trees (less than 5 months), 3.26 gram of Urea, 0.75 gram of TSP and 1.5 gram of KCl fertilizer per tree from the start, mid and end of the rain season is the best rate for fast generation of vegetative cover and root establishment
    ii. Twice of this rate reduce the efficiency of coffee varieties and should be avoided.

3. On characterizing the best varieties basing on their absorption efficiency, translocation efficiency and use efficiency
    i. The best varieties under low soil nitrogen are 13/61, BK 27 and MR 10 and farmers cultivating in areas with low nitrogen should be supplied with these varieties.
    ii. The best varieties under low phosphorus are BK 27 and 13/61, and farmers cultivating in areas with phosphorus problem in the soils should be supplied with these varieties.
    iii. The best varieties under low potassium are 13/61 and BK 27, and farmers cultivating in areas with low K should be supplied with these varieties

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# APPENDICES

**Appendix 1: Anova table summary for the Effect of applied Fertilizers (Urea, TSP and KCl) on total dry matter yield of the four Robusta coffee varieties**

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr |
|---|---|---|---|---|---|
| Robusta varieties | 3 | 1055.01 | 351.67 | 10.29 | <.001 |
| Amount of N, P and K | 2 | 232.57 | 116.28 | 3.40 | 0.052 |
| Robusta varieties by Urea, TSP and KCl fertilizers | 6 | 263.94 | 43.99 | 1.29 | 0.304 |

**Appendix 2: Anova table summary for the Total N content of the four varieties of Robusta coffee subjected to three levels of N from Urea fertilizer**

| Source of variation | d.f | s.s. | m.s. | v.r. | F pr |
|---|---|---|---|---|---|
| Robusta varieties | 3 | 6.4949 | 2.1650 | 3.57 | 0.030 |
| Amount of Urea fertilizer | 2 | 45.1456 | 45.1456 | 22.5728 | 37.21 |
| Robusta varieties by Urea fertilizer | 6 | 6.8796 | 1.1466 | 1.89 | 0.128 |

**Appendix 3: Anova table summary for the Total P content of the four varieties of Robusta coffee subjected to three levels of P from TSP fertilizer**

| Source of variation | d.f | s.s. | m.s. | v.r. | F pr |
|---|---|---|---|---|---|
| Robusta varieties | 3 | 0.136922 | 0.045641 | 12.71 | <.001 |
| Amount of TSP fertilizer | 2 | 0.508356 | 0.254178 | 70.76 | <.001 |
| Robusta varieties by TSP fertilizer | 6 | 0.058444 | 0.009741 | 2.71 | 0.040 |

**Appendix 4**: **Anova table summary for the Total K content of the four varieties of robusta coffee subjected to three levels of K from KCl fertilizer**

| Source of variation | d.f | s.s. | m.s. | v.r. | F pr |
|---|---|---|---|---|---|
| Robusta varieties | 3 | 0.2640 | 0.0880 | 0.34 | 0.797 |
| Amount of KCl fertilizer | 2 | 7.4576 | 3.7288 | 14.40 | <.001 |
| Robusta varieties by KCl fertilizer | 6 | 1.9822 | 0.3304 | 1.28 | 0.309 |

**Appendix 5**: **Anova table summary for the Nitrogen absorption efficiency (NAE) of four varieties of Robusta coffee trees subjected to three levels of N from Urea fertilizer**

| Source of variation | d.f | s.s. | m.s. | v.r. | F pr |
|---|---|---|---|---|---|
| Robusta varieties | 3 | 144.292 | 48.097 | 13.21 | <.001 |
| Amount of Urea fertilizer | 2 | 39.613 | 19.806 | 5.44 | 0.012 |
| Robusta varieties by Urea fertilizer | 6 | 64.323 | 10.721 | 2.94 | 0.029 |

**Appendix 6: Anova table summary for the Phosphorus absorption efficiency (PAE) of four varieties of Robusta coffee trees subjected to three levels of P from TSP fertilizer**

| Source of variation | d.f | s.s. | m.s. | v.r. | F pr |
|---|---|---|---|---|---|
| Robusta varieties | 3 | 0.61206 | 0.20402 | 4.33 | 0.015 |
| Amount of TSP fertilizer | 2 | 5.16954 | 2.58477 | 54.80 | <.001 |
| Robusta varieties by TSP fertilizer | 6 | 0.74933 | 0.12489 | 2.65 | 0.044 |

**Appendix 7: Anova table summary for the Potassium absorption Efficiency (KAE) of four varieties of Robusta coffee trees subjected to three levels of K from KCl fertilizer**

| Source of variation | d.f | s.s. | m.s. | v.r. | F pr |
|---|---|---|---|---|---|
| Robusta varieties | 3 | 58.128 | 19.376 | 13.66 | <.001 |
| Amount of KCl fertilizer | 2 | 12.412 | 6.206 | 4.37 | 0.025 |
| Robusta varieties by KCl fertilizer | 6 | 27.373 | 4.562 | 3.22 | 0.020 |

**Appendix 8: Anova table summary for the Nitrogen translocation efficiency (NTE) of four varieties of Robusta coffee trees subjected to three levels of N from Urea fertilizer**

| Source of variation | d.f | s.s. | m.s. | v.r. | F pr |
|---|---|---|---|---|---|
| Robusta varieties | 3 | 84.42 | 28.14 | 1.38 | 0.274 |
| Amount of Urea fertilizer | 2 | 33.42 | 16.71 | 0.82 | 0.453 |
| Robusta varieties by Urea fertilizer | 6 | 152.30 | 25.38 | 1.25 | 0.321 |

**Appendix 9: Anova summary for the Phosphorus Translocation Efficiency (PTE) of four varieties of Robusta coffee trees subjected to three levels of P from TSP fertilizer**

| Source of variation | d.f | s.s. | m.s. | v.r. | F pr |
|---|---|---|---|---|---|
| Robusta varieties | 3 | 69.37 | 23.12 | 0.66 | 0.585 |
| Amount of TSP fertilizer | 2 | 3405.43 | 1702.71 | 48.60 | <.001 |
| Robusta varieties by TSP fertilizer | 6 | 259.51 | 43.25 | 1.23 | 0.327 |

**Appendix 10: Anova summary for the Potassium Translocation Efficiency (KTE) of four varieties of Robusta coffee trees subjected to three levels of K from KCl fertilizer**

| Source of variation | d.f | s.s. | m.s. | v.r. | F pr |
|---|---|---|---|---|---|
| Robusta varieties | 3 | 753.63 | 251.21 | 2.98 | 0.054 |
| Amount of KCl fertilizer | 2 | 137.77 | 68.89 | 0.82 | 0.455 |
| Robusta varieties by KCl fertilizer | 6 | 1139.26 | 189.88 | 2.25 | 0.076 |

**Appendix 11: Anova summary for the Nitrogen use efficiency (NUE) of four varieties of Robusta coffee trees subjected to three levels of N from Urea**

| **Source of variation** | **d.f** | **s.s.** | **m.s.** | **v.r.** | **F pr** |
|---|---|---|---|---|---|
| Robusta varieties | 3 | 24830. | 8277. | 3.58 | 0.030 |
| Amount of Urea fertilizer | 2 | 8767. | 4384. | 1.90 | 0.174 |
| Robusta varieties by Urea fertilizer | 6 | 8165. | 1361. | 0.59 | 0.735 |

**Appendix 12: Anova summary for the Phosphorus Use Efficiency (PUE) of four varieties of Robusta coffee trees subjected to three levels of P from TSP fertilizer**

| **Source of variation** | **d.f** | **s.s.** | **m.s.** | **v.r.** | **F pr** |
|---|---|---|---|---|---|
| Robusta varieties | 3 | 64814853. | 21604951. | 8.71 | <.001 |
| Amount of TSP fertilizer | 2 | 6439843. | 3219921. | 1.30 | 0.293 |
| Robusta varieties by TSP fertilizer | 6 | 13199610. | 2199935. | 0.89 | 0.521 |

**Appendix 13: Anova summary for the Potassium Use efficiency (KUE) of four varieties of Robusta coffee trees subjected to three levels of K from KCl fertilizer**

| Source of variation | d.f | s.s. | m.s. | v.r. | F pr |
|---|---|---|---|---|---|
| Robusta varieties | 3 | 120694. | 40231. | 3.20 | 0.043 |
| Amount of KCl fertilizer | 2 | 58333. | 29166. | 2.32 | 0.122 |
| Robusta varieties by KCl fertilizer | 6 | 59800. | 9967. | 0.79 | 0.585 |