POTATO (*Solanum tuberosum* L.) YIELD AND QUALITY RESPONSE TO NITROGEN, PHOSPHORUS AND POTASSIUM FERTILIZER RATES IN RWANDA

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EGERTON UNIVERSITY

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DECLARATION AND RECOMMENDATION

Declaration

I declare that this thesis is my original work and has not been presented in this university or any other, for the award of a degree.

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DEDICATION

This work is dedicated to the Almighty God; my wife, Clotilde Uwamariya; and my children, Adrien Tuyihorane, Adrien Tuyiramye and Adrien Tuyishimire.

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ABSTRACT

Potato is a strategic commodity with the potential to improve food and nutrition security and to generate income in Rwanda. Despite its potential, potato intensification remains low, translating into low yield. The low yield is occasioned mainly by the decline in soil fertility. In addition, farmers adapt a blanket fertilizer recommendation rate which is not sensitive to the actual crop needs. Field experiments were conducted in Birunga, Mudende [L_1] and Buberuka, Rwerere [L_2] highlands Agro-Ecological Zones (AEZs), during season A 2017 [S_1] and B 2017 [S_2] to determine the effects of rates of N, P and K on yield and quality of potato. The experiments were laid out using a Randomized complete block design with factorial arrangement, with four replicates. Factors were N rates (N_X): (i) N_0-0 kg ha^{-1}, (ii) N_{50}-50 kg ha^{-1} (iii) N_{100}-100 kg ha^{-1}; P_2O_5 rates (P_X): (i) P_0-0 kg ha^{-1}, (ii) P_{50}-50 kg ha^{-1}, (iii) P_{100}-100 kg ha^{-1}and K_2O rates (K_x): (i) K_0-0 kg ha^{-1}and (ii) K_{50}-50 kg ha^{-1}. Data collected included growth parameters, tuber yield components and quality attributes. Analysis of variance for the data, performed using SAS-version 9.2, revealed the existence of a significantly different soil fertility gradient, between the two locations and farms within both locations. The two locational and seasonal results showed similar response patterns with regard to effects of N, P, K and their combinations. Effects of location, N, P, K and N×P×K were found to be significant on all growth, tuber yield and quality traits except number of main stems per plant, while the effect of season was significant on all growth and yield attributes and non-significant on number of main stems per plant and all potato quality traits. With regard to tuber yield, L_1, S_2, N_{100}, P_{100} and K_{50} factor levels and $N_{100}P_{100}K_{50}$ combination performed better than other treatments. $N_{100}P_{100}K_{50}$ recorded highest tuber yields: (32.73 ± 0.43) t ha^{-1} [L_1] and (29.36 ± 0.41) t ha^{-1} [L_2] and (31.05 ± 0.52) t ha^{-1} for pooled ANOVA. Contrarily to what happened at Rwerere (L_2), effects of N_{100} and N_{50} on tuber yield as well as $N_{100}P_{100}K_{50}$ and $N_{50}P_{100}K_{50}$ were not significantly different from each other at Mudende (L_1). With regard to potato quality, except $N_{100}P_{100}K_0$, $N_{50}P_{100}K_0$ and $N_0P_{100}K_0$ found suitable for making potato salad, whole boiled and canned potatoes, all other treatments (with > 1.080, > 14%, > 20% and < 0.30% of specific gravity, starch, dry matter and reducing sugar content, respectively) were qualified suitable for making French fries, chips and flakes. $N_{50}P_{100}K_{50}$ is recommended to Birunga AEZ whereas $N_{100}P_{100}K_{50}$ is recommended to Buberuka AEZ. Further studies, using a wide range of fertilizer rates, will be necessary to determine optimal combination of N, P and K nutrient rates in both locations.

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LIST OF ACRONYMS AND ABBREVIATIONS

AE	Agronomic Efficiency
ANOVA	Analysis Of Variance
AOAC	Association of Official Analytical chemists
AP	Available Phosphorus
AS	Available Sulphur
ATP	Adenosine Triphosphate
BMP	Best Management Practice
BS	Base Saturation
CAVM	College of Agriculture, Animal Sciences & Veterinary Medicine
CEC	Cation exchange capacity
CIP	Centre International de la Pomme de terre/ Potato International Centrer
CV	Coefficient of variation
DM	Dry Matter
DAE	Days After Emergence
DAP	Diammonium Phosphate
DM	Dry Matter (content)
FA	Factor Analysis
FAO	Food and Agriculture Organization (of the United Nations)
FAOSTAT	Food and Agriculture Organization of United Nations (Statistics division)
FYM	Farm Yard Manure
FTW	Fresh Tuber Weight
F_x	Farm Number x
GM	Grand Mean
GDP	Gross Domestic Product
ICSFAD	International Centre for Soil Fertility and Agricultural Development
I FDC	International Fertiliser Development Centre
IPM	Integrated Pests Management
ISAR	Institut des Sciences Agronomiques du Rwanda
K (K_x)	Potassium (Level of K_2O)
LAI	Leaf Area Index
LSD	Least Significant Difference

LTY	Large (sized) Tuber Yield
L_x	Location Number
MATY	Marketable Tuber Yield
MINAGRI	Ministry of Agriculture, Forestry and Livestock
MINALOC	Ministry of Local Government
MINECOFIN	Ministry of Finance and Economic Planning
MINIRENA	Ministry of Lands, Environment, Forests, Water and Mines
MTY	Medium (sized) Tuber Yield
N (N_X)	Nitrogen (Level [dose] of Nitrogen)
NGO	Non-Governmental Organisation
NICHE	Netherlands Initiative for capacity development in Higher Education
NSP	Number of main Stems per Plant
NTP	Number of Tubers per Plant
NUFFIC	Netherlands Organisation for International Cooperation in Education
PAR	Photosynthetically Active Radiation
P (P_X)	Phosphorus (Level [dose] of P_2O_5)
PRT	Protein (content)
RAB	Rwanda Agriculture Board
RCBD	Randomized Complete Block Design
RS	Reducing Sugars (content)
SAS	Statistical Analysis System
SG	Specific Gravity
SH	Stem Height
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SSA	Sub-Saharan Africa
ST	Starch (content)
STY	Small (sized) Tuber Yield
S_x	Season Number
TTY	Total Tuber Yield
UMATY	Unmarketable Tuber Yield
UR	University of Rwanda
VTC	Vitamin C (content)

CHAPTER ONE

INTRODUCTION

1.1 Background information

Agriculture, the major component of Rwanda's national economy, contributes one third of the Rwanda's GDP. The sector is however characterized by low productivity resulting from progressive soil fertility decline over the years which primarily results from incessant cropping without adequate addition of mined nutrients (MINAGRI, 2004; RIU, 2010; MINECOFIN, 2012). In permanent agricultural systems, soil fertility is maintained through application of organic and mineral fertilizers. In many parts of the world and especially in Sub-Saharan Africa (SSA) the availability, use, and profitability of inorganic fertilizers have been low whereas there has been an intensification of land-use and an expansion of crop cultivation onto marginal soils (IFDC, 2009).

Farmers in Rwanda rely on "the one size fits all" philosophy as a fertilization strategy to improve agricultural productivity. In Rwanda, one fertilizer recommendation applies to the whole country or a wide region (Patil, 2009; Rushemuka *et al.*, 2014). Thus, such blanket fertilizer application recommendations may lead farmers to either over-fertilize or under-fertilize, or apply imbalanced fertilizer for their soil or crop (Patil, 2011). An alternative to blanket recommendation is, site-specific fertilizer recommendation, which aims to minimize undesired effects of nutrient under- or over-application, while optimizing the supply of soil nutrients through four key principles; "4 Rs" (Right product, Right rate, Right time and Right place) (Patil, 2009; Bruulselma *et al.*, 2012). Blanket fertilizer recommendations fail to capture heterogeneity in soil fertility at landscape level. Nutrient management plans must be site-specific, tailored to the soils, landscapes, micro-climate and management objectives of the farm (Patil, 2011).

Potato is highlighted in the Crop Intensification Program (CIP) as a strategic commodity with the potential to improve food and nutrition security and generate income in Rwanda (REMA, 2009; MINAGRI, 2011). The crop is adapted to different agro-ecological conditions, has a high yield potential, a short growing period and hence ideally suitable for places where land is limited (Abalo *et al.*, 2001). Its cultivation is intensively carried out all year round in Birunga and Buberuka highlands AEZs (Rwanda) where weather and soil conditions are potentially favourable for its performance (MINAGRI, 2011). However, continuous cropping for enhanced yields removes substantial amounts of nutrients from soil. Imbalanced and inadequate use of chemical fertilizer and various cultural practices affect adversely potato yield and quality, and degrade the soil quality rapidly (Medhe *et al.*, 2012). Potato being a heavy feeder, high yields and quality necessitate an adequate supply of nutrients throughout the whole growth period (Dechassaand Schenk, 2004). Total nutrient uptake are site-specific (White *et al.*, 2007; Khan *et al.*, 2008). Potatoes require adequate and balanced quantities of macronutrients and micronutrients for optimum production (IFDC, 2009). Both low and high nutrient doses and/or ratio affect adversely crop health, tuber yield and quality (Jeuffroy *et al.*, 2002; Westermann, 2005; Mustafa *et al.*, 2012; Rytel *et al.*, 2013).

A wide variety of factors may have an impact on potato tuber yield, nutritional and processing quality (suitability for processing). These include genetic make-up factors, environmental factors and agricultural practices (fertilizer rates, irrigation, pesticide treatment, planting and harvesting time). The differences in yield and quality of potato tubers grown in various locations result from differentiated environmental conditions, especially the weather and soil features (Agblo and Scanlon, 2002). The agrotechnical treatments can influence both the yield and the technological value (a number of external and internal features determining their suitability for industrial processing) of potatoes destined for processing (Thybo *et al*., 2002).

The application of fertilizer should vary across locations and seasons due to difference in soil types, nutrient availability of the soil, moisture supply and crop variety (Dechassa and Schenk, 2004; Zelalem *et al.*, 2009). Potato growers are enormously challenged to produce enough commercial potato tubers with high quality while minimizing the environmental impact which may result from under-fertilizer application in some areas and over-fertilizer application in others (Zebarth and Rosen, 2007). Without systematic consideration of different soil types and weather diversity, soil scientists in Rwanda have failed to determine soil-specific fertilizer recommendations for the main crops of the country (including potatoes), even after so many years of soil fertility management research. Therefore, only generic and blanket recommendations are formulated and available for the entire territory of Rwanda without any consideration to the diverse AEZs and soil types (Rushemuka *et al.*, 2014).

1.2 Statement of the problem

In Rwanda, the potato crop is mainly grown by smallholder farmers and; its yield has stagnated at about 10.2 t ha-1 while the potential yield is up 40 t ha-1. The potato low productivity is predominantly occasioned by low and declining soil fertility, unavailability of clean seeds, poor market accessibility and limited financial investment, diseases and limited accessibility to high yielding varieties. However, the individual impact of each factor to low potato productivity in Rwanda is not well documented. Low fertility of soil occasioned by continuous cultivation coupled with inefficient addition of external nutrient inputs is a major constraint, affecting potato growth, tubers yield and quality. Nitrogen (N), phosphorus (P) and potassium (K) are generally known to be the major macro-nutrients in agro-ecosystems. They therefore are the first to limit potato crop production and tuber quality. Currently soil nutrient levels in Birunga and Buberuka highlands AEZs are generally low or medium in total nitrogen [(0.1-0.5)%], available phosphorus [(5-15)ppm] and exchangeable K [(0.2-0.6) meq/100g]. Limited and declining soil fertility is a major challenge for crop production in Rwanda, with nitrogen (N) and phosphorus (P) as the most limiting elements. Both the yield and quality of potato tubers are, to a large extent, dependent on nutrient rates. The fertilizer recommendation adopted in Rwanda is general (blanket); 300 kg of compound fertilizer 17-17-17 ha^{-1} supplying 51 kg ha^{-1} each of N, P_2O_5 and K_2O, and does not consider heterogeneity in soil at landscape level. The general application of fertilizers has contributed to soil fertility decline thus impeding potato growth, low tuber yields and quality. Potato yield gap in Rwanda, is occasioned mainly by the decline in fertility of soil arising from incessant cropping without adequate replenishment of mined nutrients and aggravated by the blanket fertilizer recommendations. Therefore, this research aimed at assessing potato growth, tuber yield and quality response to different levels of nitrogen, phosphorus and potassium in Birunga and Buberuka highlands agro-ecological zones (AEZs) of Rwanda. Hence this research was conducted with the following objectives;

1.3 Objectives

1.3.1 General Objective

To contribute towards food and nutrition security through application of appropriate rates of mineral fertilizers for enhanced potato yield and quality in Rwanda.

1.3.2 Specific Objectives

i. To characterize physical and chemical soil properties of Irish potato fields in Birunga and Buberuka highland AEZs of Rwanda.
ii. To determine the effects of different rates of nitrogen (N) fertilizer on growth, yield and quality of Kinigi potato variety in Birunga and Buberuka highland AEZs of Rwanda.

iii. To determine the effect of different rates of phosphorus (P) fertilizer on growth, yield and quality of Kinigi potato variety in Birunga and Buberuka highland AEZs of Rwanda.
iv. To determine the effect of potassium (K) fertilizer on growth, yield and quality of Kinigi potato variety in Birunga and Buberuka highland AEZs of Rwanda.
v. To determine the interaction effect between nitrogen, phosphorus and potassium fertilizers on growth, yield and quality of Kinigi potato variety in Birunga and Buberuka highland AEZs of Rwanda.

1.4 Hypotheses

i. Soil physical and chemical properties of Irish potato fields do not differ from each other in Birunga and Buberuka highland AEZs of Rwanda.
ii. Nitrogen fertilizer rates do not differ in their influence on growth, yield and quality of Kinigi potato variety in Birunga and Buberuka highland AEZs of Rwanda.
iii. Phosphorus fertilizer rates do not differ in their influence on growth, yield and quality of Kinigi potato variety in Birunga and Buberuka highland AEZs of Rwanda.
iv. Potassium fertilizer application does not have an effect on growth, yield and quality of Kinigi potato variety in Birunga and Buberuka highland AEZs of Rwanda.
v. There is no interaction effect between nitrogen, phosphorus and potassium fertilizers on growth, yield and quality of Kinigi potato variety in Birunga and Buberuka highland AEZs of Rwanda.

1.5 Justification of the study

The agricultural sector is the mainstay of the Rwanda's economy. Agriculture in Rwanda provides employment to about 72% of the labour force, contributes to about 33% of the Gross Domestic Product (GDP), meets 90% of the national food needs, and generates more than 70% of the country's export revenues. About 81% of all households in the country depend on agriculture (Bizoza, 2015). Given the importance of the agricultural sector and specific challenges it faces, the Government of Rwanda (GOR) undertook reforms and put in place important policies and programs.

Vision 2020 acknowledges that the most important issue retarding Rwanda's agricultural development is not land size, but low productivity associated with low and inefficient use of farm inputs (MINECOFIN, 2012). The CIP intends to promote agricultural intensification, where potato is one of eight priority crops identified by the programme. Irish potato was recommended to be grown in Birunga and Buberuka highland AEZs of Rwanda (MINAGRI, 2011). Within the two AEZs, the four districts: Burera, Musanze, Nyabihu and Rubavu, are the most productive accounting for around 60% of the national potato production. However, the average yield in the four district is still low as 11.6 t ha^{-1} (MINAGRI, 2013). The CIP Program attempts to address the concerns reflected in Vision 2020 on the reduction in productivity by emphasizing that intensification should be accompanied by a sharp increase in fertilizer use effectiveness.

Potato yield has stagnated at about 10.2 t ha^{-1} in Rwanda while the potential yield is up 40 t ha^{-1} (MINAGRI, 2011). The gap of around 30 t ha^{-1} is equivalent to a loss of Rwf 5100000 ($ 6000) for potato grower, the price of one kilogram of fresh potato being Rwf 170 ($ 0.2) at collection centre (African Potato Association, 2018). Rapid decline of soil fertility arising from continuous and intensive cultivation without adequate replenishment of mined nutrients coupled with blanket fertilizer application are major causes of low potato yield in Rwanda (RIU Rwanda, 2010). Nitrogen, phosphorus and potassium are the three nutrients that commonly limit potato yield and quality in agroecosystems (Mulubrhan, 2004); with nitrogen and phosphorus being the most limiting elements (Tening *et al.*, 2013). The agrotechnical treatments and environmental conditions applied on potato influences the yield and both the nutritional quality and the technological value of potato tubers destined for processing (Agblo and Scanlon, 2002; Singh and Kaur, 2009; Singh and Lal, 2012).

Although many investigators have studied the effect of N, P and K nutrients on growth, yield and quality of potato, they highlighted much dissimilarity in their results. Due to that, this study aimed to investigate the quantitative and qualitative performance of Kinigi potato variety under different doses of nitrogen, phosphorus and potassium fertilizers in Birunga and Buberuka highlands AEZs of Rwanda.

CHAPTER TWO
LITERATURE REVIEW

2.1 Soil fertility

The world population is growing and the United Nations expect there will be 8.9 and 11.2 billion people by 2050 and 2100, respectively. Most of these people will live in developing countries, mostly in Africa where already 20% of population is underfed or malnourished. The demand for food will increase as well as the need to produce more food on declining soil fertility, volume of water bodies and plot size of arable land per household. Globally, food production must be doubled by 2050 (Lal, 2009; Sasson, 2012). As human population continues to increase, human disturbance on the earth's ecosystem to produce food and fiber will place greater demand on soils to supply essential nutrients. Continuous cropping for enhanced yield removes substantial amounts of nutrients from soil. Imbalanced and inadequate use of chemical fertilizers, improper irrigation and various cultural practices also deplete the soil quality rapidly (Medhe *et al.*, 2012).

From agricultural point of view, soil is the collection of natural bodies occupying parts of the earth's surface that support plants, it possesses properties that are linked to a combined effect of climate and biological activities upon parent materials, as conditioned by relief, over period of time (Brady and Weil, 2002). The soil offers support to plants and acts as a reservoir of water and nutrients. The availability of nutrients in soil depends upon soil pH, organic carbon (OC) content (estimate of soil organic matter), adsorptive surfaces and other physical, chemical and biological conditions in the rhizosphere (Jiang *etal.*, 2009). Soil quality is controlled by its physical, chemical and biological properties and their interaction. Soil plays a major role in determining the sustainable productivity of an agro-ecosystem. The sustainable productivity of a soil mainly depends upon its ability to supply essential nutrients to the growing plants. The deficiency of nutrients has become major constraint to productivity, stability and sustainability of soils (Belland Dell, 2008).

Soil fertility is defined as the ability of the soil to supply, in proper amounts and forms, all the nutrients required by the crop. Fertility of soil is the most important factor which regulates growth, yield and quality of crops (Yadav, 2011). One of the specific soil functions important in promoting plant growth, yield and quality is provision of mineral nutrients available to plant roots in quantity, time, space, and form (Weil and Magdoff, 2004). Plants take their nutrients mostly from soil. It is well known that the optimum plant growth and crop yield depends not only on the total amount of nutrients present in the soil at a particular time but also on their availability which in turn is controlled by physico-chemical properties such as pH and organic carbon, cation exchange capacity, soil texture and electrical conductivity of soil (Bell and Dell, 2008). Indeed, soil characterization provides the information for our understanding of the physical, chemical, mineralogical and microbiological properties of the soils we depend on to grow crops, sustain forests and grasslands as well as support homes and society structures (De la Rosa *et al.*, 2004; De la Rosa, 2005). Soil characterization provides the basic information necessary to create functional soil classification schemes, and assess soil fertility in order to unravel some unique soil problems in an ecosystem (Hailu *et al.*, 2015; Adhanom and Toshome, 2016).

2.2 Soil fertility status in Sub-Saharan Africa

Agriculture is the main source of livelihood and income for two-thirds of Africa's population (IFDC, 2009). Limitations in organic matter and other key nutrients largely constrain agricultural productivity. Intensive cultivation without nutrient replenishment is the major driver of soil fertility degradation in Sub-Saharan Africa (SSA) (Stocking, 2003). Declining soil fertility has been identified as one of the most significant constraints to increasing food production in SSA. The depleted soil has caused average yields of crops to stagnate or even go down whereas on the other hand fertilizer consumption of SSA has stagnated at 8-12 kg ha^{-1} $year^{-1}$ since at least last ten years (FAO, 2015). In addition to inherent soil fertility constraints, continued mining of soils during the past decades has rendered even originally fertile soils low productive in SSA (Sanchez, 2002). Limited and inefficient application of mineral fertilizer coupled with mining of nutrients in the form of crop yields and crop residues, soil erosion, and insufficient recycling of nutrients are the norms rather than exceptions in many East and Southern African countries, and SSA as a whole (Thierfelder *et al.*, 2013).

2.3 Fertilizer use and soil productivity in Sub-Saharan Africa

Numerous studies show that substantial agricultural productivity gains can be achieved in SSA by increasing the use and efficiency of fertilizer (Maiangwa *et al.*, 2007). Maximizing the agronomic efficiency of the applied nutrients and thereby, improving crop productivity should be high priority in SSA (Mujeri *et al.*, 2012). Despite the growing evidence, farmers in Sub-Saharan Africa still lag behind in fertilizer use. The average fertilizer use in SSA is still the lowest at around 10 kg ha^{-1} whereas it has reached 222 kg ha^{-1} in Asia, 160 kg ha^{-1} in Oceania and 138 kg ha^{-1} in South America (Sanginga and Woomer, 2009). Lack of plant nutrients is one of the causes for low agricultural productivity and food insecurity in SSA (Sanchez, 2002). Decline of soil fertility is seen as the most important constraint to crop production in SSA (Sanchez and Jama, 2002). Most SSA farmers get low response rate from fertilizer application or relatively low yield due to inefficiency in application and/or the poor soil fertility conditions (Gregory and Bumb, 2006). The average fertilizer use (kilograms per hectare of arable land) in East African countries is also still low: 38 kg ha^{-1} in Kenya, 12.6 kg ha^{-1} in Tanzania, 10.9 kg ha^{-1} in Rwanda, 5.4 kg ha^{-1} in Burundi and 1.9 kg ha^{-1} in Uganda (World Bank, 2015).

2.4 Spatial variability of soil fertility

A number of factors determine the fertility of soils: (i) parent material, (ii) soil formation processes like weathering operating at a timescale of thousands of years, and (iii) human management operating over much shorter timescales (Abebe *et al.*, 2010). Soil fertility is a dynamic natural property and it can vary, over time and space, under the influence of natural and human induced factors. Spatial variation in soil has been recognised for many years (Medhe *et al.*, 2012). It has been viewed as consisting of two main variance components: systematic and stochastic variability.

Systematic variability is considered as a gradual or marked change in soil properties as a function of landforms, geomorphic elements, soil-forming factors and/or soil management. The variability in soils that cannot be related to any known cause is considered to be the *stochastic variability*. This unexplained heterogeneity is also termed 'random', 'chance' or noise variation (McBratney *et al.*, 2000).

Tittonell *et al.* (2005) and Minai (2015) broadly grouped factors influencing soil spatial variability into two categories: (i) Agroecological or environmental or physical category (geology/geomorphology, climate, and land use/land management subcategories) and (ii) socio-economic category (distribution of markets or market access, poverty prevalence, population growth rate or population pressure and infrastructure availability and accessibility).

Despite a generalized trend of decreasing soil fertility in SSA (Bationo, 2004), rates of depleting and replenishing soil nutrient stocks vary from one farm to another *(*Haileslassie *et al.*, 2007; Zingore *et al.*, 2007). Bucagu *et al.* (2013) and Franke *et al.*(2016) conducted field works in current Southern and Northern provinces of Rwanda, respectively found that soil properties vary spatially from a field to a larger spatial scale, depending on both intrinsic (soil formation factors, such as soil parent materials and catenal position) and extrinsic factors (such as soil management practices, farming systems, socio-economic factors, farm size and location).

Smallholder farmers having insufficient fertilizers, use them particularly on farm plots neighboring their homesteads. The scenario leads to a steep gradient of increasing fertility of soil with decreasing distance from the farmhouse (Zingore *et al.*, 2011). Such allocation of nutrient resources, coupled with inherent spatial heterogeneity in soil fertility, results in steep gradient of soil fertility between farms subjected to imbalanced nutrients supply. Zingore *et al.* (2007) also indicated the presence of prominent gradient of soil fertility generated by different agricultural practices even on small plots of land closer to the farmhouses. This spatial heterogeneity in soil fertility within and between farms affects resource use efficiencies, crop yield and quality (Tittonell *et al.*, 2008). Allocating nutrient resources on more fertile homefields than on depleted outfields culminates in a new scenario of eternalizing spatial heterogeneity of soil fertility at small (within farm), medium (between farms) and large scale (between regions and AEZs) (Zingore *et al.*, 2007). Unfertilized crop, low or unbalanced fertilization lead to depletion of soil nutrients and soil degradation due to lower soil organic matter contents (from root biomass and even above ground biomass associated with reduced crop yields). This situation leads to soil structure degradation in particular and soil quality degradation in general (Sanginga and Woomer, 2009).

2.5 Site specific nutrient management

As long as there is heterogeneity in soil fertility in an agro-ecosystem, whether natural and/or human induced, there is no such thing as a blanket guidance (uniform rate) on the amount of fertilizer to apply to fit all fertility situations (Drechsel *et al.*, 2015). Blanket fertilizer recommendation rate means a similar application rate recommended for the same crop or for different crops, over a large spatial scale. This system is still prevalent in several developing countries due to lack of high resolution tests. On the contrary, locational management of nutrient, whether founded on laboratory analysis of the nutrient content in soil or plant in a given field, matches the requirements of crops through four key principles "4 Rs" (Right product, Right rate, Right time and Right place) (Vanlauwe and Giller, 2006; IFA, 2009; Bruulselma *et al.*, 2012; IPNI, 2012; Drechsel *et al.*, 2015). It ensures that nutrients applied via fertilizers are managed according to the needs of the soil-plant system (Sapkota *et al.*, 2014). Site-specific nutrient management (SSNM) aims to optimize the supply of soil nutrients over time and space to ensures that soil health, optimum crop yield and quality can be maintained on a long-term basis (Kumar and Yadav, 2001).

2.6 Crop growth and yield response to nutrient supply

Growth is an integrative physiological trait that responds to environmental factors, which is decisive for plant fitness in any agroecosystem (Westoby *et al.*, 2002). Plants in natural ecosystem face abiotic constraints limiting their growth and yield, and finally affecting their fitness in a given agroecosystem (Korves *et al.*, 2007). In response to such limiting factors, vegetative growth stages as well as reproductive phases are the main attributes determining plant fitness in any ecosystem (Donohue *et al.*, 2009; Barto and Cipollini, 2009; Milla *et al.*, 2009). These features are under the control of complex networks integrating genetic factors and environmental factors as well as their interaction (Gilbert, 2009). Plant growth is a function of various environmental or growth factors and may be depicted by an equation as:

$$G = f(x_{1,} x_{2,}\ x_{3,} \ldots\ldots x_n)$$

where G = measure of growth and x_1, x_2, x_3,……x_n = various growth factors (Barker and Pilbeam, 2006). Plant growth (and even yield) can be explained using two laws: Liebig's law of the minimum and Mitscherlich's law of diminishing return.

Liebig's law of the minimum: the law specifies that the growth of a plant is limited by the nutrient that is in shortest supply (in relation to plant need). Once its supply is improved, the next limiting nutrient controls plant growth. This concept has been depicted in many ways. One is to imagine a barrel with staves of different heights (Figure 2.1). Such a barrel can only hold water up to the height of its shortest stave. The barrel can be full only when all its staves are of the same size (Barker and Pilbeam, 2006). Liebig's law of the minimum means that plant can also produce to its full potential when all nutrients (production factors in an enlarged sense) are at an optimal level, i.e. without any deficiencies or excesses. In order to produce high yields, plant nutrition requires a continuous effort to eliminate minimum factors and provide balanced nutrition in the optimal range. In a broader sense, the law of the minimum can be extended to include all production inputs, not only nutrients (Barker and Pilbeam, 2006).

Figure 2.1 Demonstration of the law of the minimum

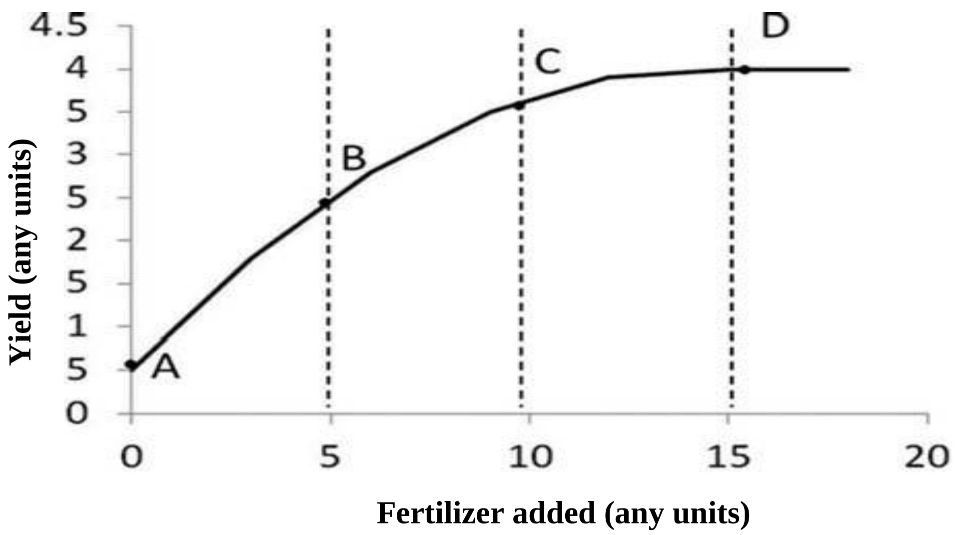
Source: Barker and Pilbeam (2006)

Mitscherlich's law of diminishing return: the law specifies that plant growth response to a limiting element is not proportional as Liebig proposed but rather follows a law of diminishing return. Thus, Mitscherlich developed a mathematical equation to express this law mathematically:

$$\frac{dy}{dx} = k\ (Y - y)$$

where *dy* is the yield increase resulting from a small addition *dx* of the limiting factor, k is a constant for a particular crop and growth factor, Y is the maximum possible yield and y is the yield under the actual condition. It means that each additional unit of fertilizer gives slightly smaller benefit than the previous unit as illustrated by the Figure 2.2 (Barker and Pilbeam, 2006; Roy *et al.*, 2006).

According to nutrient response curve, yield-fertilizer response curve shows that crop yield increases with nutrient supply, but at decreasing rate (Mitscherlich, 1909). Between A and B, efficiency is high while production is still lower than the maximum. Higher efficiency and lower production characterizes areas with low levels of nutrients. Between B and C, there is an increase in yield but at lower rate that it is between A and B; efficiency is lower while production gets higher. Between C and D, is the usual section of optimum rate, point D is equivalent to 90%–95% of maximum yield. After point D, yields do not respond to added nutrient. Sometimes, adding nutrient may lead to a decrease in yields (Dibbs, 2000; Roy *et al.*, 2006).



Source: Roy *et al.* (2006)

Figure 2.2 Crop yield and applied nutrient response curve

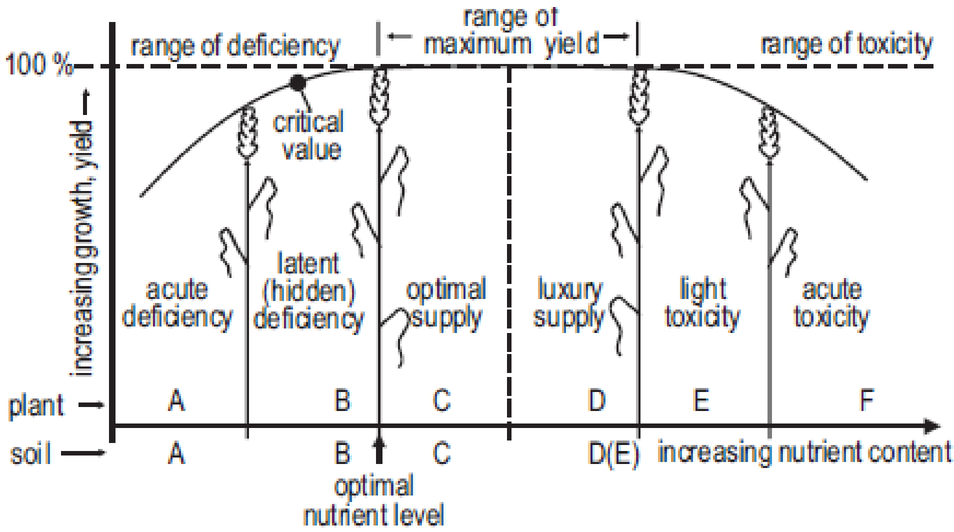
It is not easy to provide plants with exactly adequate amounts of all nutrients, and the task is made more difficult by numerous interactions between nutrients. On one hand, nutrients have their individual specific functions; on the other hand, there are also some common functions as well as interactions which can be either positive or negative (Roy *et al.*, 2006). A positive or synergistic interaction means that effect of two or more than two nutrients combined is greater than the sum of individual effects. A negative or antagonistic interaction means that effects of two or more than two nutrients is lower than the sum of individual effects. If there is no interaction, effect of two or more than two nutrient is equal to the sum of their individual effects (additive effect) (IFA *et al.*, 2016).

2.7 Dependence of plant growth and yield on nutrient supply

The status plant nutrient can vary from acute deficiency to acute toxicity. In general, three classes can be distinguished: deficient, optimal and excess (Roy *et al.*, 2006; IFA *et al.*, 2016). Conversely, a detailed classification of the nutritional status of plants, distinguishes six ranges.

Acute deficiency: characterized by reduced growth and visible deficiency symptoms. Supply of the deficient nutrient leads to an increase in growth and yields (Roy *et al.*, 2006; IFA *et al.*, 2016).

Marginal or latent deficiency (hidden hunger): characterized by deficiency symptoms which are not easily visible, reduced growth and yield. Supply of the deficient nutrient leads to an increase in growth and yields which may not be visible (Roy *et al.*, 2006; IFA *et al.*, 2016).



Source: IFA *et al.* (2016)

Figure 2.3 Dependence of plant growth and yield on nutrient supply

Optimal supply: this is the desired range. All plant nutrients are supplied at the most preferred level. It is characterized by plant with good health, growth, quality and high yields. This range is generally wide for most nutrients. Optimum supply is located above the critical concentration, which is normally associated with 90% of the maximum plant yield(Roy *et al.*, 2006; IFA *et al.*, 2016).

Luxury supply: in this range, there is no need to supply additional nutrient. Nutrient supply may not affect growth and yield, but may affects negatively plant health and quality of product (Roy *et al.*, 2006; IFA *et al.*, 2016).

Marginal or light (hidden) toxicity: characterized by a decrease in crop growth and yield due to effects of nutrient surplus or toxic substances on plant metabolism processes. Symptoms of toxicity may not be visible (Roy *et al.*, 2006; IFA *et al.*, 2016).

Acute toxicity: due to excessive supply of plant nutrients, the range is characterized by visible symptoms of toxicity, poor growth, poor yield, low quality and susceptibility to diseases; plant can even die (Roy *et al.*, 2006; IFA *et al.*, 2016).

2.8 Potato nutrient requirements

Potato plants require over 14 essential mineral elements, which include both macronutrients (N, P, K, Ca, Mg and S) and trace elements (Cl, Fe, Mn, B, Zn, Cu, Mo and Ni). These are generally acquired from the soil solution by the root system (Roy *et al.*, 2006; IFA *et al.*, 2016). The highest nutrients required in the highest quantities are the macronutrients: nitrogen, phosphorus and potassium. These macronutrients are rarely present at sufficient levels in the soil to provide an economic yield and therefore must be supplemented by the farmer (IFA, 2009; IPNI, 2012). For adequate nutrition and, to avoid mineral toxicities, the concentrations of all these elements in plant tissues must be maintained within certain limits (Roy *et al.*, 2006; IFA *et al.*, 2016). Insufficient tissue mineral concentrations limit potential growth and can affect tuber yield and quality, whereas excess mineral concentrations may inhibit growth through toxicity (Dampney *et al.*, 2002). Often, the soil solution lacks sufficient mineral elements for optimal plant growth, and to achieve maximal tuber yields, fertilizers are added to soils (Roy *et al.*, 2006; IFA *et al.*, 2016).

Potato nutrition is affected by its root system which is shallow and growth rate which is high. Therefore, a suitable and balanced supply of all nutrients is necessary for getting high potato yields (Dechassa and Schenk, 2004; Dechassa *et al.,* 2004). The application of fertilizer varies across locations due to many reasons such as difference in soil types, nutrient availability of the soil, moisture supply and variety (Dechassa and Schenk, 2004; Zelalem *et al.*, 2009). Potatoes can uptake high quantities of nutrients, particularly primary macronutrients (N, P and K). The total amount of nutrients taken up are site specific and depends on the amount of nutrients available in the soil, since plants generally take up more nutrients than required when available (White *et al.*, 2008).

According to FAO–FDCO (2004), the yield and quality of potato are affected by variety, environmental conditions, and cultural practices. Most nitrogen recommendations for potatoes in tropical and subtropical areas are in the range of 80-150 kg N ha^{-1}, phosphorus fertilizer recommendations range from 60 to 100 kg P_2O_5 ha^{-1} for most tropical areas and potash recommendations range from 60 to 300 kg K_2O ha^{-1} (but varying between 60 and 150 kg K_2O ha^{-1} in most developing countries). According to Dampney *et al.* (2002), White *et al.* (2005) and Sapkota *et al.* (2014), nutrient recommendation depends on environmental factors such as soil type, soil mineral concentrations and agronomic factors such as timing, location and chemical form of the fertilizer applied; it also depends on weather conditions and genetic factors such as longevity, growth rate and tissue mineral requirements of a potato variety. The use of chemical fertilizers mainly NPK has been increasing steadily but many times they are not applied in balanced proportions. Balanced fertilizer application is a prerequisite for getting optimum yield and quality of potato (Kushwah *et al.*, 2005). Excessive or deficient application of any required nutrient reduces tuber yield and quality (Laboski and Kelling, 2007). Optimizing N, P and K nutrient rates is necessary for enhanced potato yields and quality (Khan *et al.*, 2008).

Although many studies were conducted on the response of effect of potato growth and yield to primary macronutrients in different locations, they have pointed out much dissimilarity in the results obtained. Mugo *et al.* (2013), Zewide *et al.* (2012) and Mulubrhan (2004) recommended 90 Kg N ha^{-1}, 165 kg N ha^{-1} and 165 kg N ha^{-1}, respectively for optimum potato yields. On the other hand, Zewide *et al.* (2012), Mulubrhan (2004) and Zelalem *et al.* (2009) found that applying P_2O_5 at the rates of 60 kg ha^{-1}, 90 kg ha^{-1} and 90 kg ha^{-1}, respectively lead to optimum potato yields, while FAO–FDCO (2004) reports that optimum K_2O vary within the range of 60-150 kg ha^{-1}.

2.8.1 Effect of nitrogen on potato growth, tuber yield and quality

The application of N-fertilizer affects chlorophyll content in which in turn causes an increase in the Radiation Use Efficiency (RUE) (Pilbram *et al.*, 2009). The maximum energy from light absorption and RUE optimizes photosynthesis, and therefore biomass production and yield increase due to light penetration into different canopy layers (Haverkort *et al.*, 2007). Lecocur and Ney (2008) showed that there is a positive correlation between the total dry matter production and photosynthetic active radiation (PAR). Nitrogen application impacts the plant shoot characteristics such as leaf size, leaves direction and the ageing process of lower leaves, which in turn affect the light absorption by plants (Weiner *et al.*, 2008). The amount of intercepted radiation depends on the leaf area index which is a function of the leaf area development and duration (Yuan and Bland, 2005), all of which are affected by nitrogen. An adequate supply of nitrogen is required to achieve a canopy capable of intercepting most radiation, whereas excessive nitrogen can delay crop maturity, result in excessive vine growth (Vos and MacKerron, 2000).

Tuber yield is generally responsive to nitrogen fertilizer addition (Zebarth *et al.*, 2009). Nitrogen fertilizer application increases yield primarily through an increase in tuber mass. Fresh tuber weight increases with increasing nitrogen application rates (Bélanger *et al.*, 2002). However, bulking rates are not always affected positively by nitrogen fertilizer application; over-fertilization can result in reduced tuber yield (Bélanger *et al.*, 2002).

Nitrogen fertilizer rate may have an effect on potato quality (morphological, nutritional and processing) parameters such as size of tubers, tuber specific gravity, tuber content in dry matter and crude protein, reducing sugar, vitamin C and crude ash content (Laboski andKelling, 2007). Potato specific gravity is sometimes not affected by nitrogen fertilizer rate, or may be negatively correlated with N rate, mainly when nitrogen rate is above optimum for the crop (Laboski and Kelling, 2007). In many cases, potato specific gravity is negatively correlated with N rate (Bélanger *et al.*, 2002; Zebarth *et al.*, 2004). Nitrogen rate can also affect the nutritional quality of potato tubers. Concentration of nitrate in potato tubers generally increases with increasing rate of nitrogen (Bélanger *et al.*, 2002). Most importantly, increasing fertilizer nitrogen rate has been reported to affect tuber quality by increasing tuber concentrations of asparagine and reducing sugars, which are precursors to the production of acrylamide during frying (Gerendás *et al.*, 2007; Lea *et al.*, 2007).

The response of potato nutritional quality attributes to varying nitrogen fertilizer rates was stressed by different authors. They proved that tuber crude protein content increases with increase of nitrogen fertilizer rate till the optimum crop requirement. The positive influence of N on crude protein content is mainly due to accumulation of N content during tuber bulking stage which led to formation of more amino acids and increase in tuber protein content (Ahmed *et al.*, 2009; Yassen *et al.*, 2011; Ahmed *et al.*,2015). A similar relationship pattern was observed with potato ascorbic acid content (Lin *et al.*, 2004; Lakshmi, 2010). Davis (2005) and White *et al.* (2008) reported a negative effect of yield-enhancing methods such as increase of N fertilizer rate on potato crude ash concentration due to a ‘‘dilution effect’’, which is attributed to plant growth rates exceeding the ability of plants to acquire mineral elements.

2.8.2 Effect of phosphorus on potato growth, tuber yield and quality

The effects of P fertilization on tuber yield are thought to be a direct consequence of increased leaf area index, ground cover and radiation absorption. Because yield is dependent on photoassimilate and radiation absorption during the period of tuber initiation, P is one of the factors influencing the number of tubers found at harvest. P fertilization produces not only greater yields but also more tubers (Jenkins and Ali, 2000; Allison *et al.*, 2001; Dampney *et al.*, 2002; White *et al.*, 2005) .

Phosphorus affects plant metabolism or biological processes such as transfer of energy, processes associated with photosynthesis and respiration (Grant *et al.*, 2001). Phosphorus is also one of the major component of biological compounds such as phospholipids nucleic acids, coenzymes, and phosphoproteins (Stark and Love, 2003). Potatoes require an adequate supply in phosphorus from planting to maturity for optimum tuber set and growth rate. Phosphorus affects growth and potato yield through including leaf size and leaf area index for several weeks after emergence (Grant *et al.*, 2001).

Phosphorus influences tuber starch synthesis (Stark and Love, 2003). On soil with low to medium phosphorus content, number of tubers per plant increases with increasing phosphorus rate. According to the findings of some researchers, phosphorus application increases the proportion of large tubers while others reported that the application of P leads to an increase in the number of small tubers and a decrease in number of large tubers (Jenkins and Ali, 2000; Rosen and Bierman, 2008). Few studies reported no effect of phosphorus rate on number of tubers per potato plant (Mohr and Tomasiewicz, 2011). In general, number of main stems per plant is not influenced by phosphorus rate (Jenkins and Ali, 2000). However, Rosen and Bierman (2008) reported an increase in stem number with phosphorus application. Phosphorus is also important in starch synthesis and storage, and even in hastening crop maturity (Stark and Love, 2003).

Results on phosphorus effects on specific gravity of potato tubers were different: on soils with low phosphorus content, phosphorus application often increases tuber specific gravity while on soils with high phosphorus content, phosphorus application leads to a decrease in specific gravity (Sanderson *et al.*, 2003; Rosen and Bierman, 2008; Mohr and Tomasiewicz, 2011). Stark and Love (2003) reported that, phosphorus application can balance the negative impact of high nitrogen rates on specific gravity.

The effects of phosphorus fertilizer on potato nutritional parameters have been reported by different authors. Magali *et al.* (2017) pointed out the existence of positive relationship between crude protein content in potato tubers and progressive increase of phosphorus fertilizer levels while White *et al.* (2008) highlighted a positive effect of phosphorus level application on ascorbic acid content in potato tubers. Most metabolic processes including cell division, cell expansion, respiration, photosynthesis and proteosynthesis are reduced by phosphorus deficiency since it is a part of the structure of DNA, RNA, ATP and phospholipids in membranes (Stark and Love, 2003). Davis (2005) and White *et al.* (2008) stressed the existence of a negative relationship between effect of increased P fertilizer rate and potato crude ash concentration due to the dilution effect.

2.8.3 Effect of potassium on potato growth, tuber yield and quality

Potassium plays a critical role in enzyme activation, water use, photosynthesis, transport of sugars, nitrate reduction, protein synthesis, and starch synthesis in plants (Askegaard *et al.*, 2004). Application of potassium increases plant height, crop vigor and impart resistance against drought, frost and diseases (Brady and Weil, 2002). Potassium increases leaf expansion particularly at early stages of growth, extends leaf area duration by delaying leaf shedding near maturity. It increases both the rate and duration of tuber bulking and increases the size of tubers. So, potassium increases the aggregate yield by mainly increasing yield of medium and large sized tubers (Trehan *et al.*, 2001). Thus, potassium deficiency in soil causes serious reduction in crop yield and crops encountered with such deficiency become easily susceptible to disease and pests, damage by frost and have poor yield and quality (Umar and Moinuddin, 2001). Potassium application rate influences tuber size, specific gravity, susceptibility to black spot bruise, after-cooking darkening, reducing sugar content, fry color, and storage quality. The crucial importance of potassium in quality formation stems from its role in promoting synthesis of photosynthates and their transport to the tubers, and to enhance their conversion into starch, protein and vitamins (Laboski and Kelling, 2007). Potassium influences on quality can also be indirect as a result of its positive interaction with other nutrients (especially with nitrogen) and production practices (Johnston and Milford, 2009).

Potassium plays an important role in the transport of assimilates and nutrients. The photosynthesis products must be transported from the sources to the sinks. Potassium promotes phloem transport of photosynthates to the physiological sinks, the tubers (Askegaard *et al.*, 2004). Potassium deficiency changes carbohydrate metabolism, with negative consequences such as accumulation of reducing sugars (soluble carbohydrates) and a decrease in starch and dry matter content. It is generally known that starch content is enhanced by potassium application, so long as this is to correct potassium under-nutrition, whilst heavy doses of potassium may decrease starch content (Laboski and Kelling, 2007). The potato nutritional parameters like crude protein (Abd El-Latif *et al.*, 2011; Arafa *et al.*, 2012) and vitamin C content are improved with K application (Lakshmi, 2010; Arafa et *al.*, 2012; Haddad *et al.*, 2016). The vital importance of potassium in quality formation relies on its role in stimulating synthesis of photosynthates and to boost their conversion into starch, protein and vitamins (Bansal and Trehan, 2011). Conversely, crude ash content in potato is negatively associated with increase of K fertilizer rate due to a dilution effect. The effect is reflected by growth rate exceeding the ability of plants to acquire mineral elements (Davis, 2005; White *et al.*, 2008).

2.9 Potato quality attributes

2.9.1 Potato nutritional quality

Potato is the main source of macro and micronutrients which play a big role for the nourishment of the human body. Potatoes produce more edible energy and protein per unit area of land than any other crop. Potatoes contain approximately 80% water, 20% dry matter and less than 1% fat. Some 82% of the dry matter is composed of carbohydrate, mainly starch, with some dietary fiber and small amounts of various simple sugars (Li *et al.*, 2006). Potatoes contain low amount of protein with high biological value and is very high in comparison with other roots and tubers. Potato is low in fat, contains at least 12 essential vitamins (especially vitamin C) and ash (wide range of minerals) (Storey, 2007).

2.9.2 Potato processing quality

Potatoes are consumed fresh mainly through boiling. Nowadays, there is increase in demand of processed potato products (French fries and potato crisps). Processing industries require potatoes with specific characteristics which allow them to produce products of high quality with high consumers' preference (Li *et al.*, 2006; Storey, 2007). The most promising factors determining potato processing quality are specific gravity, dry matter, starch and sugars content. Potato processing attributes depend on factors like genotype, environmental conditions, cultural practices, postharvest factors and storage conditions (Mohammed, 2016). Specific gravity is a quick indicator of potato quality, positively related to the yield of processed potato products. To get good quality fried product, specific gravity of potatoes should be between 1.0701 and 1.0850 (Feltran *et al.*, 2004). Dry matter contributes to the quality and yield of processed products and was reported to range from 13 to 37% with the average of 24%. High dry matter in tubers leads to high yield of processed product and low oil uptake on frying (Li *et al.*, 2006). Starch is the major constituent of dry matter in potatoes, increases with increase in dry matter content and contributes up to 75% of the dry matter (Storey, 2007). Reducing sugars vary from 0.0 to 0.5% with average of 0.3% on fresh weight basis. Potatoes with high amount of reducing sugars are not suitable for processing of potato products. High amount of reducing sugar leads to the formation of acrylamide which is a byproduct of Maillard reaction and considered as potential carcinogen. It is associated to bitter taste and unfavorable brown color of the products (Zhu *et al*., 2010).

2.10 Fertilize use and potato production in Rwanda

Fertilizer rate applied in in Rwanda is still low, the average rate is estimated to a mere 10.9 kg of nutrients per hectare compared with Kenya, Tanzania, Oceania and Asia whereas it has reached 38 kg ha^{-1}, 12.6 kg ha^{-1}, 148 kg ha^{-1} and 222 kg ha^{-1}, respectively (World Bank, 2015). In Rwanda, mineral fertilizer application is mainly limited on cash crops (tea, coffee and pyrethrum). Within staple crops, fertilizers are mostly used for maize, rice and wheat as cereals, beans and soybeans as legumes, and cassava and Irish potato as root and tuber crops; the crops are considered as priority crops according to crop intensification programme (MINAGRI, 2012). Most fertilizer recommendations applied in Rwanda are blanket recommendations, often applied over huge areas or over the whole country while encompassing several agro-ecological zones. Farmers who use mineral fertilizers, mostly buy compound fertilizers which contain the three major crop nutrients (N, P and K) in the same bag (NPK fertilizers) (Olson and Berry, 2014).

Crop Intensification Program (CIP), established by Ministry of Agriculture and Animal Resources in Rwanda, considers potato as a strategic commodity with the potential to improve food and nutrition security and generate income. Its cultivation is intensively carried out all year round in Birunga and Buberuka highlands AEZs (Rwanda) where weather and soil conditions are potentially favourable for its performance (Rukundo *et al.*, 2019). Within the two AEZs, the four districts: Burera, Musanze, Nyabihu and Rubavu, are the most productive accounting for around 60% of the national potato production. The average yield in the four district is still low as 11.6 t ha^{-1} (MINAGRI, 2013). The crop alone covers around 4% of seasonal cultivated land in Rwanda. Increase in potato demand in Rwanda and in the region resulted in substantial increase of area allocated to potato production in Rwanda particularly in Birunga and Buberuka highlands AEZs (MINAGRI, 2014). Most potato growers in Rwanda are small scale-farmers who hardly realise an average yield of around 10 t ha^{-1} compared with other countries who realise easily 40 t ha^{-1}. The low yield is attributed to low and declining soil fertility (Muhinyuza *et al.*, 2012; Olson and Berry, 2014). Most small-scale farmers in Rwanda apply little or no mineral fertilizers to their crops. As results, farmers' yields are lower than they could be. Even if potato growers wish to apply mineral fertilizers, they found that most existing ffertilizer recommendations are blanket recommendations (300 kg of compound fertilizer 17-17-17 ha^{-1} supplying 51 kg ha^{-1} each of N, P_2O_5 and K_2O) which do not consider heterogeneity in soil at landscape level as they are not really tailored to address the specific reality of all farmers (Olson and Berry, 2014).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Experimental sites

Field trials were carried out on-station study, in two locations (sites) in Rwanda; Mudende location [L_1]-Rubavu districts and Rwerere location [L_2]-Burera district, located in Western and Northern Provinces, respectively; during season A 2017 (September- December, 2016) [S_1] and B 2017 (March-June, 2017) [S_2]. Both districts are characterized by steeply sloping hills, high altitude, low temperature and high rainfall. Their soils are dominated by volcanic soils but may be in association to a lesser extent, with other soils such as alisols identified in part of Burera (MINIRENA, 2004). The volcanic soils of Rwanda are volcanic ash or andosols (FAO, soil map of the World) or andisols (USDA soil taxonomy) (Birasa *et al.*, 1990). Mudende location - Rubavu district (L_1) is located at a latitude of 1°35′43.5″S and a longitude of 29°23′24″E, at 2356 m above sea level. The district is part of Birunga highlands agro-ecological zone. It receives about 1200 mm to 1350 mm of rainfall and has a mean temperature of 21^{o}C. The district has an average density of 1039 inhabitants /km^2 and the mean size of cultivated land per household is less than 0.3 ha (Rubavu District, 2013). Rwerere location-Burera district (L_2) is located at a latitude of 1^{o}29′27.42′′S and a longitude of 29^{o}52′40.44′′E, at an altitude of 2062 m. The district is part of Buberuka and Birunga highlands agro-ecological zones. It receives rainfall amount estimated at1400 mm and has a range of temperature of 9^{o} C - 29^{o} C. The district has an average density of 522 inhabitants /km^2 and the mean size of cultivated land per household is 0.39 ha (Burera District, 2013).

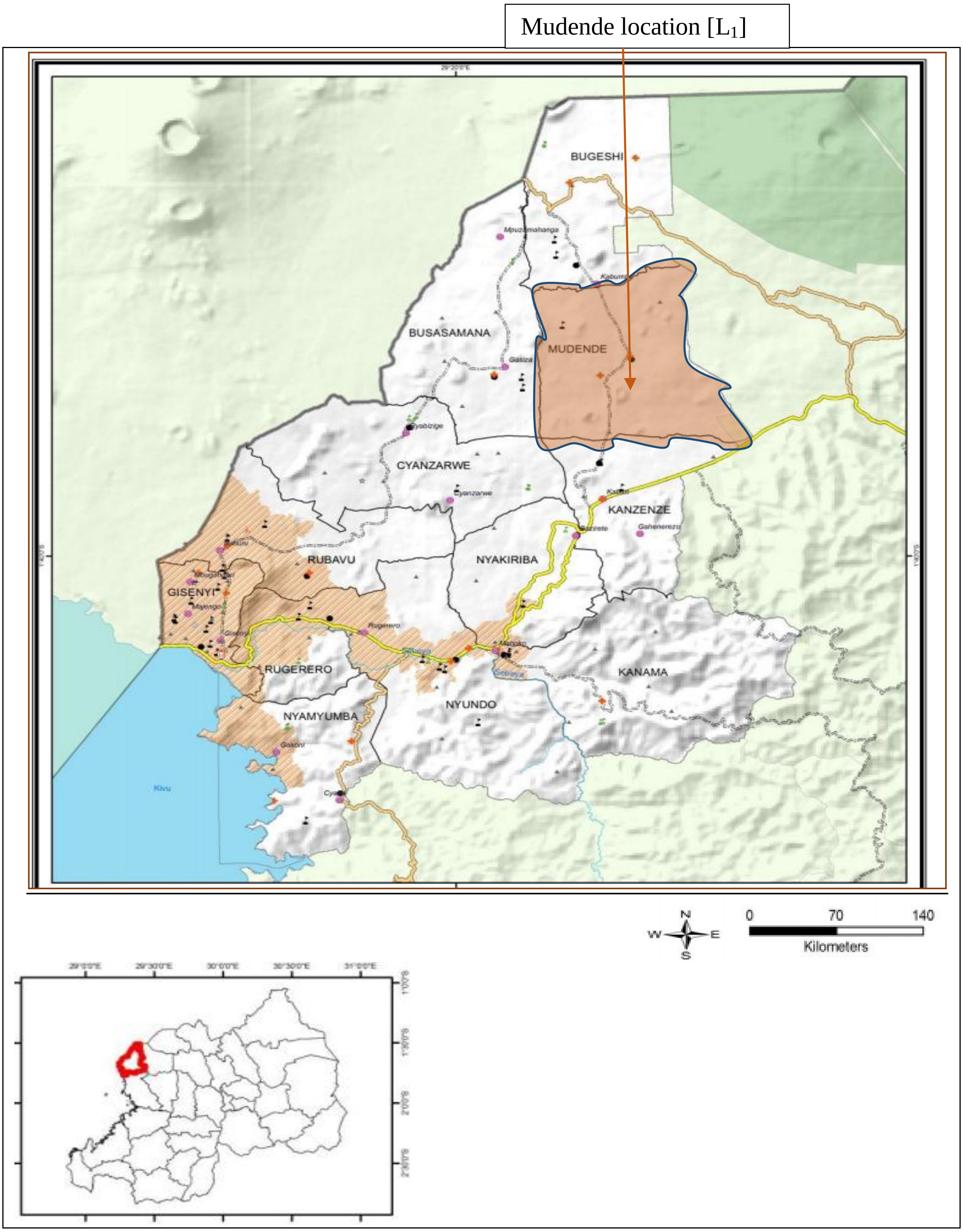


Figure 3.1 Experimental sites: Mudende location [L_1] (Rubavu district)

Source: Administrative map of Rubavu district (National Institute of Statistics of Rwanda [NISR], 2012)

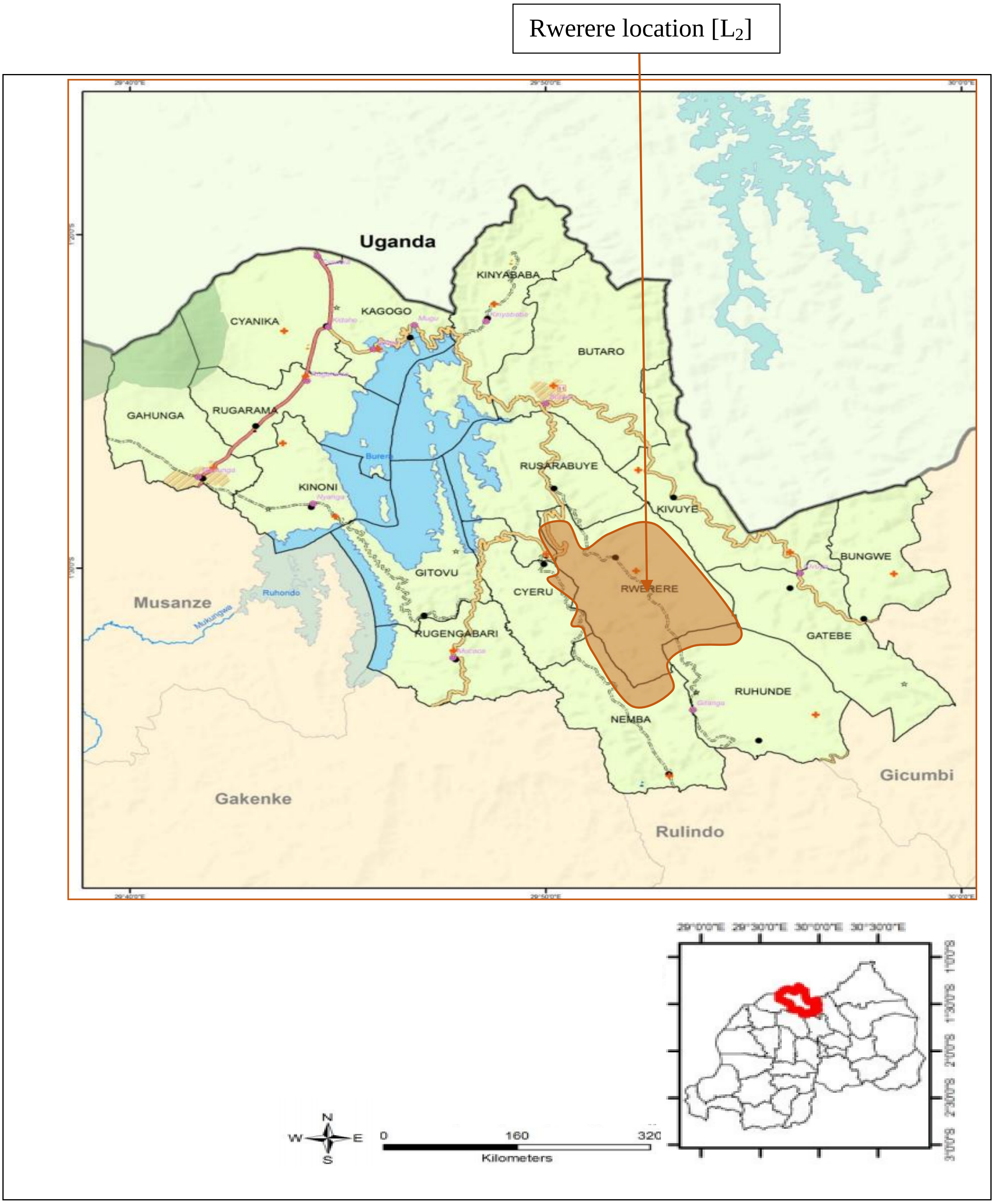


Figure 3.2 Experimental sites: Rwerere location [L_2] (Burera district)

Source: Administrative map of Burera district (National Institute of Statistics of Rwanda [NISR], 2012)

Table 3.1 Selected meteorological data for the study sites characterization

Season	Month	Location: Mudende temperatures-Rubavu station Max (°C)	Min (°C)	Mean (°C)	Range (°C)	Rwerere temperatures-Ruhunde station Max (°C)	Min (°C)	Mean (°C)	Range (°C)
Season A2017	September	25.82	12.15	18.98	13.67	26.42	13.39	19.90	13.03
	October	25.16	11.754	18.45	13.41	25.57	13.10	19.34	12.47
	November	25.80	11.69	18.75	14.11	25.65	12.92	19.29	12.73
	December	26.27	13.20	19.73	13.07	26.21	13.49	19.85	12.72
Season B2017	March	25.65	11.25	18.45	14.40	24.07	13.08	19.57	12.89
	April	24.15	10.12	17.14	14.03	25.77	12.67	19.22	13.10
	May	26.34	10.50	18.42	15.84	25.80	12.71	19.25	13.09
	June	27.04	11.73	19.39	15.31	26.58	13.20	19.89	13.38

Source: Rwanda meteorological centre, Kigali/Rwanda: 2016/2017 data.
Rubavu and Ruhunde are the nearest meteorological stations of Mudende and Rwerere study sites, respectively.

Table 3.2 Soil properties of the experimental sites

Property	**Value** Mudende (L_1)	Rwerere (L_2)
Textural class	Sandy loam	Sand clay loam
Bulk density	1.42	1.57
pH-H_2O	6.42	5.93
Organic C (%)	5.33	3.89
Total N (%)	0.28	0.20
Available P (ppm)	9.00	8.67
K (meq/100g)	0.47	0.34
Ca (meq/100g)	8.44	7.18
Mg (meq/100g)	2.24	2.02
CEC (meq/100g)	18.53	17.40
Base saturation (%)	61.91	56.56
Available S (ppm)	8.34	7.89

According to Bruce and Rayment (1982) scale, the pH of soil of Mudende was slightly acidic while the pH of the soil of Rwerere was modelately acidic. According to Landon (1991), the soil of Mudende was medium in organic carbon, total nitrogen, available phosphorus and sulphur, exchangeable bases, CEC and high in base saturation content whereas the soil of Rwerere was low in organic carbon and total nitrogen content; medium in available phosphorus and sulphur, exchangeable bases, CEC and base saturation content. In general, Mudende location was more fertile than Rwerere as it exhibited higher values in nearly all soil chemical parameters tested.

3.2 Treatment combination and experimental design

The three factors under study were N, P_2O_5 and K_2O (nutrients) rates. There were three levels or rates of N, P_2O_5 and two levels of K_2O. Table 3.3 shows the 18 treatment combinations while Table 3.4 shows how the 18 treatments were randomized within each replication.

Table 3.3 Treatment combination

Treatment combination		
1. $N_0P_0K_0$ (control)	7. $N_{50}P_0K_0$	13. $N_{100}P_0K_0$
2. $N_0P_0K_{50}$	8. $N_{50}P_0K_{50}$	14. $N_{100}P_0K_{50}$
3. $N_0P_{50}K_0$	9. $N_{50}P_{50}K_0$	15. $N_{100}P_{50}K_0$
4. $N_0P_{50}K_{50}$	10. $N_{50}P_{50}K_{50}$	16. $N_{100}P_{50}K_{50}$
5. $N_0P_{100}K_0$	11. $N_{50}P_{100}K_0$	17. $N_{100}P_{100}K_0$
6. $N_0P_{100}K_{50}$	12. $N_0P_{100}K_{50}$	18. $N_{100}P_{100}K_{50}$

The experiments were carried out in two locations using a Randomized Complete Block Design (RCBD) with factorial arrangement (3 × 3 × 2). The number of replicates was four in each location and Kinigi variety was used as test crop.A plot of (2.8 × 1.8) m^2 was used as an experimental unit and adjacent plots were separated by guard-rows of 0.6 m. The treatments were allocated randomly on each replicate (Table 3.4). Urea and triple super phosphate (Balton Rwanda-Balton CP Group, United Kingdom) were applied to supply nitrogen and phosphorus at rates of 0, 50 and 100 kg ha^{-1} (0, 50 and 100 indices, respectively) while muriate of potash (Balton Rwanda-Balton CP Group, United Kingdom) was applied to supply K_2O at rates of 0 and 50 kg ha^{-1} (0 and 50 indices, respectively).

Table 3.4 Experimental lay out

Mudende location (L_1)[Rubavu district]				**Rwerere location (L_2) [Burera district]**			
Rep 1	**Rep 2**	**Rep 3**	**Rep 4**	**Rep 1**	**Rep 2**	**Rep 3**	**Rep 4**
$N_{50}P_0K_0$	$N_0P_{50}K_0$	$N_0P_{100}K_{50}$	$N_oP_{50}K_{50}$	$N_{50}P_0K_0$	$N_{50}P_{100}K_{50}$	$N_{100}P_{100}K_0$	$N_{100}P_{50}K_{50}$
$N_0P_0K_0$	$N_{50}P_{50}K_0$	$N_{50}P_{100}K_{50}$	$N_{50}P_{50}K_{50}$	$N_{100}P_0K_0$	$N_{100}P_{100}K_{50}$	$N_0P_{100}K_0$	$N_{100}P_{50}K_0$
$N_{100}P_0K_0$	$N_{100}P_{50}K_0$	$N_{100}P_{100}K_{50}$	$N_{100}P_{50}K_{50}$	$N_0P_0K_0$	$N_{100}P_{100}K_0$	$N_{50}P_{100}K_0$	$N_{50}P_{50}K_{50}$
$N_0P_0K_{50}$	$N_oP_{50}K_{50}$	$N_0P_0K_0$	$N_0P_{100}K_0$	$N_{50}P_{50}K_0$	$N_0P_{100}K_{50}$	$N_{100}P_{100}K_{50}$	$N_0P_{50}K_0$
$N_{50}P_0K_{50}$	$N_{50}P_{50}K_{50}$	$N_{50}P_0K_0$	$N_{50}P_{100}K_0$	$N_{100}P_{50}K_0$	$N_0P_{100}K_0$	$N_0P_{100}K_{50}$	$N_{50}P_{50}K_0$
$N_{100}P_0K_{50}$	$N_{100}P_{50}K_{50}$	$N_{100}P_0K_0$	$N_{100}P_{100}K_0$	$N_0P_{50}K_0$	$N_{50}P_{100}K_0$	$N_{50}P_{100}K_{50}$	$N_oP_{50}K_{50}$
$N_0P_{50}K_0$	$N_0P_0K_{50}$	$N_0P_{50}K_0$	$N_0P_{100}K_{50}$	$N_{50}P_0K_{50}$	$N_{50}P_{50}K_{50}$	$N_{100}P_{50}K_{50}$	$N_0P_0K_0$
$N_{50}P_{50}K_0$	$N_{50}P_0K_{50}$	$N_{50}P_{50}K_0$	$N_{50}P_{100}K_{50}$	$N_{100}P_0K_{50}$	$N_{100}P_{50}K_{50}$	$N_oP_{50}K_{50}$	$N_{50}P_0K_0$
$N_{100}P_{50}K_0$	$N_{100}P_0K_{50}$	$N_{100}P_{50}K_0$	$N_{100}P_{100}K_{50}$	$N_0P_0K_{50}$	$N_{100}P_{50}K_0$	$N_{50}P_{50}K_{50}$	$N_0P_0K_{50}$
$N_0P_{50}K_{50}$	$N_0P_{100}K_0$	$N_0P_0K_{50}$	$N_0P_0K_0$	$N_{50}P_{100}K_{50}$	$N_oP_{50}K_{50}$	$N_{100}P_0K_0$	$N_{100}P_0K_{50}$
$N_{50}P_{50}K_{50}$	$N_{50}P_{100}K_0$	$N_{50}P_0K_{50}$	$N_{50}P_0K_0$	$N_{100}P_{100}K_{50}$	$N_0P_{50}K_0$	$N_0P_0K_0$	$N_{100}P_0K_0$
$N_{100}P_{50}K_{50}$	$N_{100}P_{100}K_0$	$N_{100}P_0K_{50}$	$N_{100}P_0K_0$	$N_0P_{100}K_{50}$	$N_{50}P_{50}K_0$	$N_{50}P_0K_0$	$N_{50}P_0K_{50}$
$N_0P_{100}K_0$	$N_0P_{100}K_{50}$	$N_0P_{100}K_0$	$N_0P_0K_{50}$	$N_{50}P_{50}K_{50}$	$N_{50}P_0K_{50}$	$N_{100}P_0K_{50}$	$N_{100}P_{100}K_{50}$
$N_{50}P_{100}K_0$	$N_{50}P_{100}K_{50}$	$N_{50}P_{100}K_0$	$N_{50}P_0K_{50}$	$N_{100}P_{50}K_{50}$	$N_{100}P_0K_{50}$	$N_0P_0K_{50}$	$N_{100}P_{100}K_0$
$N_{100}P_{100}K_0$	$N_{100}P_{100}K_{50}$	$N_{100}P_{100}K_0$	$N_{100}P_0K_{50}$	$N_oP_{50}K_{50}$	$N_{100}P_0K_0$	$N_{50}P_0K_{50}$	$N_{50}P_{100}K_{50}$
$N_0P_{100}K_{50}$	$N_0P_0K_0$	$N_oP_{50}K_{50}$	$N_0P_{50}K_0$	$N_{50}P_{100}K_0$	$N_0P_0K_{50}$	$N_{100}P_{50}K_0$	$N_0P_{100}K_0$
$N_{50}P_{100}K_{50}$	$N_{50}P_0K_0$	$N_{50}P_{50}K_{50}$	$N_{50}P_{50}K_0$	$N_{100}P_{100}K_0$	$N_0P_0K_0$	$N_0P_{50}K_0$	$N_{50}P_{100}K_0$
$N_{100}P_{100}K_{50}$	$N_{100}P_0K_0$	$N_{100}P_{50}K_{50}$	$N_{100}P_{50}K_0$	$N_0P_{100}K_0$	$N_{50}P_0K_0$	$N_{50}P_{50}K_0$	$N_0P_{100}K_{50}$

Rep: replication

3.3 Soil characterization

Soil sampling and analysis of physical and chemical soil properties were done to characterize Irish potato fields in Birunga and Buberuka highland AEZs of Rwanda.

3.3.1 Soil sampling

Soil samples from farms were collected before the onset of season A 2017, short rainy season (September-December, 2016). The farms were identified using a stratified sampling method. Twelve composites samples were collected from 12 farms per location (2 farms per cell counted among major producers of potato), where the farms represented potato fields in each location and were considered as treatments. Each composite sample was replicated three times. Sampling was done following a Z-shaped sampling pattern, at a depth of 0-30 cm using an auger 75 mm in diameter. Sampling, bulking, drying, sieving and storing were done as described by Okalebo *et al.* (2002).

3.3.2 Soil physical characterization

Soil particle size determination

Fifty grams of air-dried and sieved (< 2 mm) soil samples were weighed. The soil samples were saturated with distilled water and 10 mL of 10% calgon solution were added. After10 minutes, the suspensions was transferred to the dispersing cups and 300 mL of tap water were added. The suspensions were shacked overnight on reciprocating shaker (Model E5850, Eberbach). Calculation of percentages of different soil particles and determination of soil textural classes were done as outlined by Okalebo *et al.* (2002).

Bulk density

Using core method, samples were taken by driving a cylindrical metal (corer) into the undisturbed soil at a depth of 20-30cm. The samples were oven-dried (using soil drying oven, Model SDO-350) at 105°C for about 24 hours and weighed. The bulk density was equal to soil mass over core volume (Okalebo *et al.*, 2002).

3.3.3 Soil chemical characterization

Soil pH

The pH was determined using the 1:2.5 ratio of soil: water. Six grams of air-dried and sieved (2 mm) samples were put in two sets of clean plastic bottles. To each set, 15mL of distilled water were added and shaken for 30 minutes in a reciprocating mechanical shaker(Model E5850, Eberbach), allowed to stand for 30 minutes before reading the pH of the soil suspension on pH meter (YSI pH1200) (Okalebo *et al.*, 2002).

Available phosphorus

The Mehlich 3 soil test method was used to determine the available P. Two grams of air-dried ground and sieved (2 mm) soil samples were extracted using 20 mL of Mehlich 3 extracting solution. The mixtures were shaken on reciprocating shaker (Pro Digital Linear Shaker SK L330) at 200 rpm for five minutes, then filtered through filter papers. The filtrates were thereafter analyzed for phosphorus colorimetrically using a blank and standard solutions containing known concentration of phosphorus and prepared in the Mehlich 3 extracting solution. The colour was developed in calibrating (standards) solutions under conditions used for the soil extracts and their absorbances were read on a spectrophotometer (JENWAY 7315) at 882 nm wavelength. A plot of absorbance as a function of concentration was drawn and the concentration of phosphorus in each soil extract (unknown or treatment) was found out using the standard curve already drawn (Mehlich, 1984).

Organic carbon

Wet oxidation method which involves complete oxidation of soil organic carbon (OC), using concentrated H_2SO_4 and $K_2Cr_2O_7$ (Potassium dichromate), was used. The unused $K_2Cr_2O_7$ was titrated against ferrous ammonium sulphate. 0.5g of air-dried and sieved soil was weighed into a set of clean conical flasks. 5 mL of 1N $K_2Cr_2O_7$were added to each and swirled gently; 7.5 mL of 36N H_2SO_4 were rapidly added and the mixture was allowed to stand. Distilled water and a drop of mixed indicator were added. The content was thereafter titrated with 0.2N ammonium ferrous sulphate until the colour changed from dirty brown to bright green end point (Okalebo *et al.*, 2002).

Cation Exchange Capacity (CEC)

Ten grams of soil samples were extracted with a total volume of about 250 mL of 1M NH_4OAc (ammonium acetate) solution at pH 7 such that the maximum exchange occurs between the $NH_4^+$and cations originally occupying exchange sites on the soil surface. The exchange solution leached out all the cations in a soil. The amount (in the extract) of exchangeable K and Na was determined by flame photometry (Flame Photometer: Model 410-Classic); Ca and Mg by Atomic Absorption Spectrophotometry (Spectrophotometer: Model WFX-210 AAS). Adsorbed NH_4^+ in the soil was leached with 1M KCl, using a total volume of about 125 ml. The leachate solution was used to determine NH_4^+concentration, colorimetrically as outlined by Okalebo *et al.* (2002).

Base saturation percentage

Percentage base saturation was calculated by dividing the sum of exchangeable bases with the CEC, using the following formula established by Okalebo *et al.* (2002):

$$\text{Base saturation (\%)} = \frac{(\text{Ca} + \text{Mg} + \text{K} + \text{Na}) \times 100}{\text{CEC}}$$

Total Nitrogen

Oven-dried soil samples (70^{o}C) (using soil drying oven, Model SDO-350) and sieved (< 0.25 mm) were safely stored in polythene containers. Soil samples measuring 0.3 ± 0.001 g were used for total nitrogen content determination using Kjeldahl digestion (China semi-auto Kjeldahl N analyser TP-KDN) with concentrated sulphuric acid, followed by steam distillation and titration. Thereafter, the total nitrogen contents in soil samples were analysed colorimetrically as outlined by Okalebo *et al.* (2002).

Micronutrients (Cu, Zn, Fe and Mn) extraction

Diethylenetriaminepentaacetic acid (DTPA) extractable micronutrients in soil samples were determined as described by Lindsay and Norvell (1978). The extractant containing 0.005M DTPA, 0.01M $CaCl_2.H_2O$ and 0.1 M TEA (triethanolamine) and adjusted to pH 7.3 was used. 20 g of air-dried soil were mixed with 40 ml of extracting solution and shaken for two hours and then filtered. The micronutrients Cu, Zn, Fe and Mn were determined by AAS, using appropriate standards.

Extractable sulphur

Extractable sulphur was analyzed using the turbidimetric method as described by Moberg (2000). Twenty five mL of sulphur extracting solution (stock solution) was added in 100 mL plastic bottle containing 5 g air-dried soil sample then shaken for 30 minutes and filtered. Ten mL of the filtrate was pipetted and 10 mL of the acid seed solution was added in the pipetted sample. Then 5 mL of the turbdimetric reagent was added in each of the filtrate and allowed to stand for 20 minutes. Sulphur was determined in the filtrates by spectrophotometry at wavelength of 535 nm (Moberg, 2000).

3.4 Agronomic practices

Land preparation: all agricultural practices associated with land preparation were adequately done to guarantee optimum conditions for plant emergence, penetration of plant roots and free drainage of water.

Crop test: Kinigi variety was used as crop test during the field trials. It is a CIP variety (CIP 378699.2), with medium late maturity, red skin colour, light yellow fresh colour and round shape (Rukundo *et al.*, 2019). It is preferred by potato growers, processors and consumers in Rwanda due to its specific traits: disease resistance ability, high yield (up to15.0 t ha^{-1} as average) and specific gravity (starch and dry matter content), long shelf life, good storability and high processing efficiency (Muhinyuza *et al.*, 2012; Rukundo *et al.*, 2019).

Tuber-seed planting: well-sprouted tubers of medium and homogenous seed size were planted at a spacing of 70 cm between the rows and 30 cm within the rows and to a depth of 10 cm. One tuber-seed was planted per hole and tubers were covered with soil layer.

Fertilizer application: full P and K and half of N were applied at the time of planting, while the remaining half N was top dressed at 14 days after emergence. Fertilizers were uniformly spread within 10 cm diameter of the planting hole before depositing tuber seed or around the plant depending on the period of application time. The seeds/plants were never in direct contact with the fertilizer.

Weeding: weeding was done by hand hoeing 14 days after emergence.

Ridging (earthing up): ridging was done 28 days after emergence (DAE) by hand hoeing and digging soil adjacent to the crop and using the dug soil to cover the tubers and emerging stem parts.

Pests and diseases management: late and early blight were controlled using Mancozeb® (dose of 30g per 15 L, sprayed once per week).

3.5 Agronomic parameters measurement

Data were obtained from eight (8) plants in the middle two rows of each plot (entire plot minus the guard rows) from a sampling area measuring $(1.4 \times 1.2)\ m^2$.

3.5.1 Growth parameters measurements

(i) *Number of main stems per plant*: physical counting was done 15 and 30 days after emergence (DAE).

(ii) *Stem height:* measurements were taken using a tape measure as the height from the ground to the highest point of the plant at 30, 50 and 70 DAE.

(iii) *Leaf area index (LAI):* was calculated by the formula developed by Watson (1947).

$$\text{LAI} = \frac{\text{Total leaf area of the crop}}{\text{Total ground area under the crop}}$$

$$\text{Total leaf area of the crop} = \frac{\text{A} \times \text{N}}{10{,}000}$$

where A is leaf area (cm^2) of one branch and N is number of branches per plant. Leaf area was measured using LI-3100C leaf area meter at the period of 30, 50 and 70 DAE.

3.5.2 Tuber yield parameter measurements

(i) *Number of tubers per plant:* physical counting was done after pulling out tubers, at harvesting.

(ii) *Average tuber weight:* was measured using an electronic balance and expressed in grams.

(iii) *Tuber grade yield*: size grading of tubers was done after harvesting. Tubers were grouped in three tuber diameter classes, using potato size grading machine. Large (big) size: >60 mm, medium size: 30-60 mm and small size: <30 mm were weighed separately and values converted into t ha^{-1}.

(iv) *Total tuber yield:* was calculated as wet weight of all tuber grades per plot put together andconverted into t ha^{-1}.

(v) Marketable tuber yield: was calculated as sum of medium and large tuber yields expressed into t ha^{-1}.

(vi) Unmarketable tuber yield: was calculated as sum of small, diseased and damaged tuber yields expressed into t ha^{-1}.

(vii) Agronomic efficiency (AE): was calculated using the formulae cited by Mosier *et al.* (2004).

$$\text{Agronomic efficiency of X (AEx)} = \frac{(\text{Yx} - \text{Yc})}{\text{X}a}$$

where Y refers to yield of potato, x and c refer to fertilized and control plots, respectively and Xa is the quantity of nutrient added.

3.6 Analysis of potato nutritional quality attributes

3.6.1 Crude ash determination

Crude ash was determined by incineration of a known weight of samples in muffle furnace (Gallenkamp, FM 3) using method No 930.05 (AOAC, 2005). Cleaned marked silica crucibles were placed in the oven set at 105^oC for 1 hour. They were cooled in a desiccator and quickly weighed. About 2.00 g of sample were weighed and added into the crucibles. The crucibles containing samples were placed into the furnace set at 600^oC and the temperature was allowed to rise gradually and ashing was done for 4 hours. The furnace was switched off and allowed to cool to about 100^oC before transferring into desiccators for cooling down to room temperature. The crucibles were quickly weighed one by one immediately after removing from the desiccator as they are hydroscopic.

$$\text{Ash (\%)} = \frac{\text{weight after ashing X 100}}{\text{weight of the sample}}$$

3.6.2 Crude protein content

Analysis of protein was done using the method described by AOAC (2000). 0.5 g of dried ground potato tuber samples were put in a 100 mL digestion tube, 20 mL concentrate H_2SO_4 was added and then selenium was added as catalyst. The samples were put in a digester till the white fumes appeared and the samples became clear and colorless. 50 mL of 4% boric acid and indicator were put in an Erlenmeyer flask of 250-500 ml considered as receiver. Then, the receiver was placed on the distillation unit (China semi-auto Kjeldahl N analyser TP-KDN). The tip of the condenser was extended below the surface of acid solution. To the digest were added 100 mL and 70 mL of water and 50% NaOH, respectively and then distillation started. NaOH was in excess to neutralize all sulfuric acid and to ensure complete release of ammonia. Distillation was done until all ammonia was completely released or approximately above or equal to 150 mL of distillate was obtained. Thereafter the distillate was titrated with standardized 0.1N hydrochloric acid until the first appearance of pink colour. The volume of HCl used was recorded.

$$\text{Protein (\% or g per 100 g)} = \text{Total nitrogen (\%) X 6.25}$$

3.6.3 Ascorbic acid content

Ascorbic acid (vitamin C) content was determined by spectrophotometry method as described by (AOAC, 2005), using 2, 4-dinitrophenylhydrazine. 10 g of drypotato tuber samples were extracted and homogenized with freshly prepared6% metaphosphoric acid, then centrifuged at 6,000 x g for 10minutes at 4°C and filtered using an ordinary Whatman No. 1 filter paper followed by further filtration using 0.45 µm or 0.2 µm filter paper for the final working solution. Both filtrations were carried out under vacuum conditions. Using a volumetric flask, 25 mL of working calibrators of standard ascorbic acid solutions (0.10, 0.40, 0.80, 1.20, 2.0, 3.0 and 4.0 mg/dL) were prepared using 6% metaphosphoric acid.

Triplicate samples of 1.2 mL of both the clear supernatant extract and the working calibrators were pipetted into 13 x 100 mm Teflon-lined screw–cap test tubes, and 1.2 mL of the 6% metaphosphoric acid were placed into two separate tubes used as blanks. 0.4 mL of dinitrophenylhydrazine-thiourea-copper sulfate (DTCS) reagent was added to all tubes. After capping and mixing the contents, tubes were incubated in a water bath at 37ºC for 3 hours. Tubes were removed from the water bath and chilled for 10 minutes in an ice bath. 2.0 mL of cold sulfuric acid (12 mol/L) were added to all tubes while mixing slowly and the contents were capped and mixed in a vortex mixer (the temperature of the mixture could not exceed room temperature). The spectrophotometer (JENWAY 7315) was adjusted with the blank to read zero at 520 nm, and the calibrators and unknowns were read. The concentration of each working calibrator was plotted versus absorbance values and the concentrations of unknowns (research treatments) were obtained from the standard (calibration) curve.

3.7 Analysis of potato processing quality attributes

3.7.1 Dry matter and moisture percent

One kilogram of tubers was sliced and put into oven (Soil drying oven, Model SDO-350) at 100°C for 48 hours. After cooling, the moisture content (%) was determined as the loss of mass after drying. The dry matter percent was calculated following the procedure outlined by (Hassanabadi and Hassanpanah, 2003).

3.7.2 Specific gravity

Specific gravity (SG) was measured by weighting 5 kg of tubers in air and water, using a portable handheld balance (FA11FAOE7Q955NAFAMZ). It was calculated by use of the equation below.

$SG = \frac{a}{a-b}$, where, a is weight in air and b is weight in water (Dinesh *et al.*, 2005).

3.7.3 Starch content

As there is a relation between specific gravity and starch percent, the percentage of starch was calculated from the specific gravity using the following equation depicted by (Yildrim and Tokusoglu, 2005):

$Starch\ (\%) = 17.546 + 199.07 \times (\text{Specific gravity} - 1.0988)$, where specific gravity was determined as previously indicated. According to Mohammed (2016), this formula showed high accuracy as the difference between measured starch content and the calculated from the regression equation was not significant, specific gravity of potatoes is commonly used by the potato processing companies as a trustable tool for estimation of starch content.

3.7.4 Reducing sugars

The Lane and Eynon titration method using Fehling's solution was used for estimation of reducing sugars (RS) (AOAC, 2000) no 925.35. Ten grams of sample were diluted with 100 ml distilled water, agitated thoroughly to dissolve all suspended particles and afterward filtered with Whatman no 541in a 250 ml volumetric flask. From filtrate, 10 ml of diluted HCl was added and boiled for 5 min. The resultant solution was cooled and neutralized with 10% NaOH and made up to volume in a 250 ml volumetric flask using 3 drops of phenolphthalein as an indicator. The solution was titrated against Fehling's solution using 3 drops of methylene blue as an indicator and readings were recorded at the brick red end point and calculation was done using the formula below:

$$\text{RS (\%)} = \frac{4.95\ \text{(Factor)} \times 250\ \text{(Dilution)} \times 100}{\text{Weight of the sample} \ \times \text{Titre} \times 1000}$$

3.8 Data analysis

Analysis of variance for data collected on soil parameters; growth, yield, and tuber quality attributes was done using a general linear model (PROC *GLM*) of SAS Version 9.2 (SAS, 2008) since the data were continuous. The normality test was performed using Capability Procedure (Proc Capability). The t-test was used to compare group means for agronomic efficiency analysis. Individual location analyses were done separately and later a combined analysis across locations was done. Homogeneity of residual variances was tested prior to a combined analysis over seasons and locations using Bartlett's test(Steel *et al.*, 1997). The treatment effects were tested for significance using ANOVA F-test at 5%. An F-protected Least Significant Difference (F-protected LSD or FPLSD) (P=0.05) was used for mean separation. The strength of the relationship between selected soil attributes; fertilizer rates, potato growth and tuber yield parameters were determined by regression models development and Pearson's correlation coefficient analysis (Pearson, 1938). Principal component analysis (PCA) was used to reduce the dimensionality of a multivariate data to two or three principal components, which were easily visualized graphically. Factor analysis (FA) was used to discover simple patterns in the pattern of relationships among the variables and the factor loadings were categorized as strong (> 0.75), moderate (0.50 to 0.75) and weak (0.30-0.50) based on absolute loading values (Liu *et al.*, 2003).

The model for locational ANOVA is depicted by the equation below:

$Y_{fghijk} = \mu + S_f + R_g + \alpha_h + (S\alpha)_{fg} + \beta_i + (S\beta)_{fi} + \gamma_j + (S\gamma)_{fj} + (\alpha\beta)_{hi} + (S\alpha\beta)_{fhi} + (\alpha\gamma)_{hj} + (S\alpha\gamma)_{fhj} + (\beta\gamma)_{ij} + (S\beta\gamma)_{fhj} + (\alpha\beta\gamma)_{hij} + (S\alpha\beta\gamma)_{fhij} + \varepsilon_{fhijk}$

where:

μ is an overall mean,

α_h is the effect of the h^{th} level of factor α,

β_j is the effect of the i^{th} level of factor β,

γ_j is the effect of the j^{th} level of factor γ,

R_g is the effect of g^{th} replicate,

S_f are the effects of f^{th} season,

$(S\alpha)_{fh}$, $(S\beta)_{fi}$ and $(S\gamma)_{fj}$ are the interaction effects between each factor and season,

$(\alpha\beta)_{hi,}$ $(\alpha\gamma)_{hj}$, (β γ)ij, $(\alpha\beta\gamma)_{hij}$ are the interaction effects between the two or three factors,

$(S\alpha\beta)_{fhi}$, $(S\alpha\gamma)_{fhj}$, $(S\beta\gamma)_{fij}$, $(S\alpha\beta\gamma)_{fhij}$ are the interaction effects between the two or three factors and season,

ε_{fhijk} is random error term and

Y_{fhijk} is overall observation.

Regarding the experiment,

α = N; β= P_2O_5; γ= K_2O;

h, i and j are levels of N, P_2O_5 and K_2O rates applied (h=i= 0, 50, 100 and j= 0, 50; equivalent to 0, 50 and 100 kg ha^{-1}, respectively),

R is replicate (g=1, 2, 3, 4) and S is season (f= 1, 2).

The model for pooled ANOVA used is depicted by the equation:

$Y_{fghijkl} = \mu + L_f + S_g + R_h + \alpha_i + (LS)_{fg} + (L\alpha)_{fi} + (S\alpha)_{gi} + \beta_j + (L\beta)_{fj} + (S\beta)_{gj} + \gamma_k + (L\gamma)_{fk} + (S\gamma)_{gk} + (\alpha\beta)_{ij} + (L\alpha\beta)_{fij} + (S\alpha\beta)_{gij} + (\alpha\gamma)_{ik} + (L\alpha\gamma)_{fik} + (S\alpha\gamma)_{gik} + (\beta\gamma)_{jk} + (L\beta\gamma)_{fjk} + (S\beta\gamma)_{gjk} + (\alpha\beta\gamma)_{ijk} + (L\alpha\beta\gamma)_{fijk} + (S\alpha\beta\gamma)_{gijk} + \varepsilon_{fghijkl}$

where:

μ is an overall mean,

α_i is the effect of the i^{th} level of factor α,

$\beta_j$is the effect of the j^{th} level of factor β,

γ_k is the effect of the k^{th} level of factor γ,

R_h is the effect of h^{th} replicate,

L_f and S_g are the effects of f^{th} location and g^{th} season, respectively,

$(LS)_{fg}$ is the interaction effect between location and season;

$(L\alpha)_{fi}$, $(L\beta)_{fj}$, $(L\gamma)_{fk}$,$(S\alpha)_{gi}$, $(S\beta)_{gj}$ and $(S\gamma)_{gk}$ are the interaction effects between each factor and location or season,

$(\alpha\beta)_{ij,}$ $(\alpha\ \gamma)_{ik}$, $(\beta\ \gamma)jk$, $(\alpha\beta\gamma)_{ijk}$ are the interaction effects between the two or three factors,

$(L\alpha\beta)_{fij}$, $(L\alpha\ \gamma)_{fik}$, $(L\beta\ \gamma)_{fjk,}$ $(L\alpha\beta\gamma)_{fijk}$, $(S\alpha\beta)_{gij}$, $(S\alpha\ \gamma)_{gik}$, $(S\beta\ \gamma)_{gjk}$, $(S\alpha\beta\gamma)_{gijk}$ are the interaction effects between the two or three factors and location or season,

$\varepsilon_{fgijklm}$ is random error term and

$Y_{fgijklm}$ is overall observation.

Regarding the experiment,

α = N; β= P_2O_5; γ= K_2O;

i, j and k are levels of N, P_2O_5 and K_2O rates applied (i=j= 0, 50, 100 and k= 0, 50; equivalent to 0, 50 and 100 kg ha^{-1}, respectively),

R is replicate (h=1, 2, 3, 4), L is location (f=1, 2) and S is season (g= 1, 2).

CHAPTER FOUR

RESULTS

4.1 Soil characterization

Data depicting soil physical and chemical characterization are presented in Table 4.1 [Mudende location], Table 4.2 [Rwerere location] and Table 4.3 [Mudende and Rwerere locations] as described in the section below.

4.1.1 Soil physical characteristics

Regarding soil texture, the particle size distribution was dominated by sand fraction (67.59% [Mudende] and 63.70% [Rwerere] as means). Then, 100% of the soil samples in Mudende [Mudende] and Rwerere [Rwerere] locations fell in the sandy loam and sand clay loam textural classes, respectively. Samples of Mudende location had higher percentage of sand (67.59%) than the ones of Rwerere (63.70%) while samples of Rwerere had more clay (20.31%) and silt (15.99%) than samples of Mudende (18.13% of clay and 13.75% of silt) location. The results revealed that the effect of location on clay, silt and sand content was significant ($p < 0.05$). The results also revealed that there were significant ($p < 0.05$) differences for silt and sand content and no significant differences ($p > 0.05$) for clay content between farms at Mudende location. The results depicted significant ($p < 0.05$) differences between potato farms for clay content at Rwerere location while no significant ($p > 0.05$) differences were detected between them for sand and silt content. The bulk densities of the soils in both study areas varied from 1.42 to 1.61g cm^{-3}; with 1.55 g cm^{-3} and 1.42 gcm^{-3} as maximum and minimum values at Mudende and 1.69 and 1.52 as maximum and minimum values at Rwerere. The mean value was high at Rwerere (1.61) and low at Mudende (1.47). The results revealed also that location and potato farm had significant ($p < 0.05$) influences on soil bulk density.

4.1.2 Soil chemical characteristics

The pH mean values for Mudende location and Rwerere location were 6.03 and 5.92, respectively. pH of 33.33% [Mudende] and 66.67% [Rwerere] soil samples fluctuated in the range of 5.50-6.00 whereas pH of the rest soils fell in the range of 6.00-6.50. The mean values of organic carbon (OC) were 4.11% [Mudende] and 3.71% [Rwerere]. Then, OC of 50% [Mudende] and 75% [Rwerere] soil samples fell in the range of (2.0-4.0)% whereas OC of the rest of soil samples oscillated within the range of (4.0-10.0)%. The mean values of total nitrogen (TN) were 0.22% [Mudende] and 0.20% [Rwerere]. Total nitrogen of 25%

[Mudende] and 75% [Rwerere] soils fell within the range of (0.10-0.20) % while TN of the rest samples fluctuated in the range of (0.20-0.50)%. The mean values of available P were 7.92 ppm [Mudende] and 7.68 ppm [Rwerere]. Phosphorus of the total soil samples fell in the range of (5.00-15.00) ppm. The mean values of exchangeable Ca were 6.45 meq/100g [Mudende] and 6.22 meq/100g [Rwerere]. Exchangeable Ca of 25.00 % samples were below 4.0 meq/100g whereas it fluctuated within the range of (4.00-10.00) meq/100g for the rest. The mean values of exchangeable Mg were 1.65 meq/100g [Mudende] and 1.58 meq/100g [Rwerere]. Magnesium content of 25.00 % of soil samples fell below 0.50 meq/100g whereas it oscillated within the range of (0.50-4.00) meq/100g for the rest. The mean values of K were 0.35 meq/100g [Mudende] and 0.33 meq/100g [Rwerere]. Potassium content of all soil samples fluctuated within the range of (0.20-0.60) meq/100g. The mean values of Na were 0.30 meq/100g [Mudende] and 0.31 meq/100g [Rwerere]. Sodium content of 58.33% and 41.67% of soil samples fell in the ranges of (0.10-0.30) meq/100g and (0.30-0.70) meq/100g, respectively.

The mean values of CEC were 15.61 meq/100g [Mudende] and 16.48 meq/100g [Rwerere]. Cation exchange capacityof 25% soil samples fluctuated within the range of (5.00-15.00) meq/100g whereas it fell in the range of (15.00-25.00) meq/100g for the rest of samples. The mean values of base saturation were 54.82% [Mudende] and 50.35% [Rwerere]. Base saturation of 66.67% [Mudende] and 100.00% [Rwerere] fell in the range of (20.00-60.00)% while it was greater than 60% for the rest of soil samples. Available S of all samples fell within the range of (6.00-10.00) ppm with the mean values of 7.61 ppm [Mudende] and 7.44 ppm [Rwerere]. Extractable Cu of all samples fluctuated within the range of (0.30-0.80) ppm with 0.35 ppm [Mudende] and 0.34 ppm [Rwerere] as means and extractable Fe of all samples oscillated within the range of (4.00-6.00) ppm with 5.19 ppm [Mudende] and 5.28 ppm [Rwerere] as means. The mean values of extractable Mn were 3.07 ppm [Mudende] and 3.05 ppm [Rwerere]. Manganese of 91.67% [Mudende] and 100% [Rwerere] soil samples fluctuated within the range of (1.20-3.5) ppm while it oscillated within the range of (3.50-6.00) ppm for the rest. The mean values of extractable Zn were 0.97 ppm [Mudende] and 0.84 ppm [Rwerere]. Zn of 75.00% [Mudende] and 83.33% [Rwerere] soil samples fell in the range of (0.50-1.00) ppm whereas it fluctuated in the range of (1.00-3.00) ppm for the rest of samples. The results revealed that potato farm had significant ($p< 0.05$) effect on all soil parameters within location, and location had significant ($p < 0.05$) effect on all soil parameters except Na and Mn soil content (Table 4.3).

Table 4.1 Soil physical and chemical properties at Mudende location [L_1] at the beginning of the study

Treat.	**Clay (%)**	**Silt (%)**	**Sand (%)**	**BD(gcm^{-3})**	**pH**	**OC (%)**	**TN (%)**	**AP (ppm)**	**Ca (meq/100g)**	**Mg (meq/100g)**
Farm (F)1	18.17 ± 0.03^{a}	13.57± 0.30^{d}	68.26 ± 0.33^{a}	1.45d ± 0.00^{e}	6.39 ± 0.17a	4.61 ± 0.11c	0.27 ± 0.00^{b}	6.00 ± 0.00^{c}	7.39 ± 0.31^{b}	2.05 ± 0.00^{ab}
F2	18.13 ± 0.01^{ab}	14.28 ± 0.01^{c}	67.59 ± 0.01^{b}	1.47 ± 0.00^{cd}	6.05 ± 0.03b	3.86 ± 0.02e	0.21 ± 0.00^{cde}	6.33 ± 0.08^{c}	7.05 ± 0.00^{b}	1.96 ± 0.00^{b}
F3	18.09 ± 0.03^{b}	14.32 ± 0.03^{bc}	67.59 ± 0.01^{b}	1.47 ± 0.00^{cd}	5.83 ± 0.20bcd	3.50 ± 0.02f	0.21 ± 0.00^{cde}	8.50 ± 0.14^{ab}	7.04 ± 0.00^{b}	1.99 ± 0.00^{b}
F4	18.09 ± 0.03^{b}	14.33 ± 0.04^{bc}	67.59 ± 0.01^{b}	1.50 ± 0.00^{bc}	5.72 ± 0.11cd	3.45 ± 0.03f	0.19 ± 0.01^{def}	8.75 ± 0.14^{ab}	3.76 ± 0.17^{c}	0.49 ± 0.00^{c}
F5	18.13 ± 0.01^{ab}	14.28 ± 0.00^{c}	67.59 ± 0.01^{b}	1.45 ± 0.00^{de}	6.01 ± 0.02bc	3.88 ± 0.00e	0.23 ± 0.00^{c}	8.00 ± 0.29^{b}	7.04 ± 0.01^{b}	1.97 ± 0.00^{b}
F6	18.17 ± 0.03^{a}	14.90 ± 0.32^{ab}	66.93 ± 0.34^{c}	1.42 ± 0.02^{e}	6.42 ± 0.16a	5.33 ± 0.12a	0.28 ± 0.00^{b}	9.00 ± 0.29^{a}	8.44 ± 0.24^{a}	2.24 ± 0.10^{a}
F7	18.09 ± 0.03^{b}	13.66 ± 0.37^{d}	68.25 ± 0.34^{a}	1.55 ± 0.00^{a}	5.70 ± 0.03cd	3.36 ± 0.09f	0.19 ± 0.01^{ef}	8.25 ± 0.38^{ab}	3.62 ± 0.18^{c}	0.45 ± 0.00^{c}
F8	18.13 ± 0.01^{ab}	13.95 ± 0.34^{cd}	68.25 ± 0.34^{a}	1.45 ± 0.00^{de}	6.06 ± 0.02b	4.26 ± 0.07d	0.23 ± 0.00^{c}	6.42 ± 0.08^{c}	7.05 ± 0.00^{b}	1.96 ± 0.01^{b}
F9	18.13 ± 0.01^{ab}	14.28 ± 0.00^{c}	67.59 ± 0.01^{b}	1.53 ± 0.02^{b}	5.58 ± 0.19cd	3.43 ± 0.02f	0.17± 0.01^{f}	8.08 ± 0.51^{b}	3.73 ± 0.06^{c}	0.42 ± 0.01^{c}
F10	18.13 ± 0.01^{ab}	14.95 ± 0.33^{a}	66.92 ± 0.33^{c}	1.47 ± 0.02^{cd}	6.13 ± 0.02ab	4.43 ± 0.00cd	0.21 ± 0.01^{cde}	8.67 ± 0.08^{ab}	7.06 ± 0.06^{b}	1.96 ± 0.01^{b}
F11	18.13 ± 0.01^{ab}	14.27 ± 0.01^{c}	67.59 ± 0.01^{b}	1.47 ± 0.02^{cd}	6.07 ± 0.12b	4.26 ± 0.07d	0.22 ± 0.00^{cd}	8.58 ± 0.08^{ab}	7.08 ± 0.05^{b}	2.06 ± 0.00^{ab}
F12	18.17 ± 0.03^{a}	14.91 ± 0.32^{ab}	66.92 ± 0.34^{c}	1.45 ± 0.03^{de}	6.42 ± 0.17a	5.01 ± 0.11b	0.31 ± 0.03^{a}	8.50 ± 0.50^{ab}	8.12 ± 0.06^{a}	2.24 ± 0.10^{a}
Maximum	18.17	14.95	68.26	1.55	6.42	5.33	0.28	9.00	8.44	2.23
Minimum	18.09	13.57	66.92	1.42	5.58	3.36	0.17	6.00	3.62	0.42
Mean	18.13	14.31	67.59	1.47	6.03	4.11	0.22	7.92	6.45	1.65
LSD	0.07	0.61	0.57	0.04	0.31	0.20	0.01	0.83	0.41	0.19
CV (%)	0.24	2.25	0.5	1.50	3.07	2.86	3.76	6.17	3.78	6.95

Mean followed by the same letter(s) within each column do not differ statistically (p= 0.05).

Treat.: treatment; pH: potential of hydrogen, OC: organic carbon, BD: bulk density, TN: total nitrogen, AP: available phosphorus, Ca: calcium, Mg: magnesium.

Table 4.1 Continued

Treat.	K (meq/100g)	Na (meq/100g)	CEC (meq/100g)	BS (%)	S (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Zn (ppm)
Farm (F)1	0.28 ± 0.01[cd]	0.33 ± 0.02[abc]	18.27 ± 0.42[a]	55.68 ± 0.60[cd]	8.28 ± 0.35[ab]	0.39± 0.02[a]	5.62 ± 0.11[a]	3.47 ± 0.04[a]	1.08 ± 0.03[b]
F2	0.28 ± 0.02[d]	0.30 ± 0.00[def]	15.90 ± 0.06[c]	60.53 ± 0.22[a]	7.53 ± 0.02[cde]	0.34 ± 0.00[bcd]	5.29 ± 0.00[bc]	2.97 ± 0.02[cd]	0.94e ± 0.01[f]
F3	0.32 ± 0.00[bcd]	0.28 ± 0.00[efg]	15.77 ± 0.07[c]	61.13 ± 0.25[a]	7.29 ± 0.02[edf]	0.34 ± 0.00[cd]	5.01 ± 0.00[cd]	2.87 ± 0.02[de]	0.90 ± 0.00[fg]
F4	0.32 ± 0.00[bcd]	0.27 ± 0.01[g]	11.50 ± 0.29[d]	41.21 ± 0.87[f]	7.20 ± 0.00[ef]	0.32 ± 0.01[d]	4.99 ± 0.00[d]	2.52 ± 0.02[f]	0.85 ± 0.00[hi]
F5	0.31 ± 0.00[bcd]	0.30 ± 0.00[cdef]	16.80 ± 0.06[b]	57.30 ± 0.24[bc]	7.37± 0.01[edf]	0.35 ± 0.00[bc]	5.40 ± 0.01[ab]	3.00 ± 0.05[bcd]	0.95 ± 0.01[def]
F6	0.55 ± 0.03[a]	0.36 ± 0.02[a]	18.53 ± 0.38[a]	61.91 ± 0.99[a]	8.34 ± 0.35[a]	0.39 ± 0.02[a]	5.69 ± 0.10[a]	3.62 ± 0.07[a]	1.12± 0.03[ab]
F7	0.28 ± 0.01[cd]	0.26 ± 0.01[g]	11.00 ± 0.29[d]	41.40 ± 0.92[f]	6.96 ± 0.17[f]	0.32 ± 0.00[d]	4.81 ± 0.03[d]	2.50 ± 0.14[f]	0.88 ± 0.01[gh]
F8	0.28 ± 0.02[d]	0.31 ± 0.00[cde]	15.97 ± 0.09[c]	60.72 ± 0.39[a]	7.32 ± 0.06[edf]	0.35 ± 0.00[bc]	5.31 ± 0.00[b]	3.07 ± 0.02[bc]	0.98 ± 0.01[cde]
F9	0.36 ± 0.00[b]	0.28 ± 0.00[fg]	10.00 ± 0.22[e]	46.56 ± 1.05[e]	6.94 ± 0.15[f]	0.32 ± 0.00[d]	4.82 ± 0.03[d]	2.72 ± 0.06[e]	0.82 ± 0.01[i]
F10	0.32 ± 0.00[bcd]	0.31 ± 0.00[bcd]	18.00 ± 0.40[a]	53.80 ± 0.91[d]	7.93 ± 0.03[abc]	0.37 ± 0.00[ab]	5.41 ± 0.00[ab]	3.47 ± 0.02[a]	1.00 ± 0.01[cd]
F11	0.33 ± 0.00[bc]	0.31 ± 0.00[bcd]	16.90 ± 0.12[b]	57.76 ± 0.66[b]	7.80 ± 0.02[bcd]	0.35 ± 0.00[bcd]	5.40 ± 0.01[ab]	3.17 ± 0.09[b]	1.00 ± 0.00[c]
F12	0.55 ± 0.03[a]	0.34 ± 0.02[ab]	18.60 ± 0.40[a]	59.85 ± 0.27[a]	8.40 ± 0.34[a]	0.39± 0.02[a]	5.67 ± 0.10[a]	3.50 ± 0.03[a]	1.14 ± 0.04[a]
Maximum	0.55	0.36	18.60	61.91	8.40	0.39	5.69	3.62	1.14
Minimum	0.28	0.26	10.08	41.21	6.94	0.32	4.81	2.50	0.82
Mean	0.35	0.30	15.61	54.82	7.61	0.35	5.28	3.07	0.97
LSD	0.04	0.03	0.77	2.08	0.53	0.02	0.30	0.18	0.05
CV (%)	7.40	5.27	2.92	2.24	4.15	4.53	3.32	3.45	3.06

Mean followed by the same letter(s) within each column do not differ statistically (p= 0.05).

Treat.: treatment; K: potassium, Na: sodium, CEC: cation exchange capacity, BS: base saturation, AS: available sulfur, Cu: copper, Fe: iron, Mn: manganese, Zn: zinc.

Table 4.2 Soil physical and chemical properties at Rwerere location [L_2] at the beginning of the study

Treat.	Clay (%)	Silt (%)	Sand (%)	BD(gcm^{-3})	pH	OC (%)	TN (%)	AP (ppm)	Ca (meq/100g)	Mg (meq/100g)
Farm (F)1	20.26 ± 0.01^{bc}	15.73 ± 0.34^{b}	64.01 ± 0.33^{a}	1.69 ± 0.01^{a}	5.53 ± 0.17ed	3.32 ± 0.03d	0.15 ± 0.00^{e}	8.75 ± 0.14^{ab}	3.74 ±0.16^{e}	0.47 ± 0.00^{d}
F2	20.25 ± 0.01^{c}	16.09 ± 0.01^{ab}	63.66 ± 0.01^{ab}	1.69 ± 0.01^{a}	5.55 ± 0.03ed	3.33 ± 0.00d	0.015 ± 0.00^{e}	7.75 ± 0.14^{d}	3.99 ± 0.00^{e}	0.47 ± 0.00^{d}
F3	20.29 ± 0.01^{bc}	16.08 ± 0.00^{ab}	63.63 ± 0.01^{ab}	1.62 ± 0.01^{bc}	5.83 ± 0.01cd	3.52 ± 0.05c	0.19 ± 0.01^{c}	7.83 ± 0.36^{d}	7.08 ± 0.00^{c}	1.98 ± 0.00^{b}
F4	20.42 ± 0.07^{a}	16.00 ± 0.06^{ab}	63.59 ± 0.01^{ab}	1.60 ± 0.01^{cd}	6.13 ± 0.17bc	3.88 ± 0.05b	0.18 ± 0.01^{cd}	6.58 ± 0.22^{e}	7.16 ± 0.08$^{b c}$	2.02 ± 0.00^{b}
F5	20.27± 0.01^{bc}	16.09 ± 0.01^{ab}	63.65 ± 0.01^{ab}	1.62 ± 0.01^{bc}	5.87 ± 0.01bcd	3.56 ± 0.03c	0.19 ± 0.01^{c}	7.83 ± 0.08^{d}	7.02 ± 0.01^{c}	1.98 ± 0.00^{b}
F6	20.41 ± 0.06^{a}	16.08 ± 0.08^{ab}	63.51 ± 0.02^{b}	1.52 ± 0.02^{e}	6.50 ± 0.03a	4.23 ± 0.06a	0.28 ± 0.00^{a}	9.20 ± 0.23^{a}	7.67 ± 0.34^{a}	2.22 ± 0.17^{a}
F7	20.2 5 ± 0.01^{c}	15.75 ± 0.34^{ab}	64.00 ± 0.34^{a}	1.65 ± 0.01^{b}	5.57 ± 0.19ed	3.41 ± 0.05cd	0.15 ± 0.01^{de}	6.08 ± 0.08^{ef}	3.73 ± 0.17^{e}	0.47 ± 0.00^{d}
F8	20.25 ± 0.01^{c}	15.75 ± 0.32^{ab}	64.00 ± 0.33^{a}	1.65 ± 0.01^{b}	5.58 ± 0.19ed	3.47 ± 0.05cd	0.15 ± 0.02^{de}	7.75 ± 0.14^{d}	4.99 ± 0.00^{d}	1.07 ± 0.01^{c}
F9	20.29 ± 0.01^{bc}	16.07 ± 0.01^{ab}	63.63 ± 0.01^{ab}	1.57 ± 0.00^{d}	6.18 ± 0.17b	4.01 ± 0.03a	0.24 ± 0.01^{b}	5.75 ± 0.38^{f}	7.45 ± 0.27^{abc}	2.22 ± 0.17^{a}
F10	20.41 ± 0.06^{a}	16.01 ± 0.07^{ab}	63.57 ± 0.01^{ab}	1.57 ± 0.00^{d}	5.93 ± 0.01bc	3.89 ± 0.02b	0.20 ± 0.02^{c}	8.08 ± 0.22^{bcd}	7.18 ± 0.00^{abc}	2.02 ± 0.00^{b}
F11	20.27 ± 0.01^{bc}	16.08 ± 0.00^{ab}	63.65 ± 0.01^{ab}	1.60 ± 0.01^{cd}	5.92 ± 0.01bc	3.79 ± 0.10b	0.20 ± 0.01^{c}	8.02 ± 0.13^{cd}	7.03 ± 0.00^{c}	1.98 ± 0.00^{b}
F12	20.35 ± 0.01^{ab}	16.16 ± 0.00^{a}	63.49 ± 0.01 ^{b}	1.52 ± 0.02^{e}	6.40 ± 0.10a	4.09 ± 0.04a	0.28 ± 0.02^{a}	8.58 ± 0.36^{abc}	7.62 ± 0.28^{ab}	2.05 ± 0.00^{ab}
Maximum	20.42	16.16	64.01	1.69	6.50	4.23	0.28	9.20	7.67	2.22
Minimum	20.25	15.73	63.49	1.52	5.53	3.33	0.15	5.75	3.73	0.47
Mean	20.31	16.00	63.70	1.61	5.92	3.71	0.20	7.68	6.22	1.58
LSD	0.09	0.42	0.44	0.034	0.33	0.12	0.03	0.69	0.49	0.19
CV (%)	0.26	1.56	0.41	1.24	3.26	1.89	8.73	5.28	4.64	7.16

Mean followed by the same letter(s) within each column do not differ statistically ($p= 0.05$).

Treat.: treatment; pH: potential of hydrogen, OC: organic carbon, BD: bulk density, TN: total nitrogen, AP: available phosphorus, Ca: calcium, Mg: magnesium.

Table 4.2 Continued

Treat.	K (meq/100g)	Na (meq/100g)	CEC (meq/100g)	BS (%)	S (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Zn (ppm)
Farm (F)1	0.40 ± 0.00^{bc}	0.26 ± 0.00^{e}	12.66 ± 0.44^{d}	37.76 ± 0.83^{d}	6.46 ± 0.16^{e}	0.30 ± 0.00^{c}	4.85 ± 0.06^{e}	2.75 ± 0.01^{ef}	0.68 ± 0.02^{gh}
F2	0.32 ± 0.00^{d}	0.27 ± 0.00^{de}	13.00 ± 0.29^{cd}	38.57 ±1.00^{cd}	6.48 ± 0.22^{e}	0.30 ± 0.00^{c}	4.83 ± 0.06^{e}	2.65 ± 0.10^{f}	0.64 ± 0.02^{h}
F3	0.32 ± 0.00^{d}	0.29 ± 0.00^{d}	17.03 ± 0.09^{b}	56.74 ± 0.30^{ab}	7.48 ± 0.03^{cd}	0.33 ± 0.01^{b}	5.25 ± 0.01^{cd}	3.05 ± 0.00^{dc}	0.78 ± 0.01^{def}
F4	0.22 ± 0.00^{e}	0.28 ± 0.00^{de}	17.20 ± 0.06^{b}	56.88 ± 0.31^{ab}	7.50 ± 0.00^{cd}	0.34 ± 0.00^{b}	5.29 ± 0.01^{d}	2.90 ± 0.00^{de}	0.84 ± 0.01^{c}
F5	0.32 ± 0.00^{d}	0.28 ± 0.00^{de}	17.00 ± 0.12^{b}	56.40 ± 0.3 4^{b}	7.50 ± 0.00^{cd}	0.32 ± 0.00^{bc}	5.03 ± 0.01^{ab}	3.05 ± 0.00^{dc}	0.80 ± 0.00^{cde}
F6	0.47 ± 0.03^{a}	0.38 ± 0.02^{a}	18.57 ± 0.52^{a}	58.20 ±1.06^{a}	8.15 ± 0.23^{a}	0.39 ± 0.02^{a}	5.63 ± 0.21^{a}	3.49 ± 0.09^{a}	1.07 ± 0.03^{a}
F7	0.21 ± 0.00^{e}	0.27± 0.00^{de}	13.67 ± 0.44^{c}	34.78 ± 0.81^{e}	7.28 ± 0.13^{d}	0.32 ± 0.00^{bc}	4.94 ± 0.01^{e}	2.65 ± 0.10^{f}	0.73 ± 0.01^{fg}
F8	0.38 ± 0.00^{c}	0.28 ± 0.00^{de}	16.57 ± 0.09^{b}	39.91± 0.20^{c}	7.39 ± 0.03^{cd}	0.32 ± 0.00^{bc}	4.958 ± 0.01^{ed}	2.75e ± 0.00^{f}	0.74 ± 0.01^{ef}
F9	0.22 ± 0.00^{e}	0.37± 0.02^{a}	18.40 ± 0.50^{a}	56.43 ± 0.99^{ab}	7.56 ± 0.03^{bcd}	0.37 ± 0.00^{a}	5.31 ± 0.01^{bc}	3.47 ± 0.02^{b}	0.94 ± 0.00^{b}
F10	0.34 ± 0.00^{d}	0.31 ± 0.00^{c}	17.40 ± 0.06^{b}	56.56 ± 0.19^{ab}	7.89 ± 0.33^{abc}	0.39 ± 0.02^{a}	5.55 ± 0.21^{ab}	3.06 ± 0.00^{dc}	0.98 ± 0.03^{b}
F11	0.32 ± 0.00^{d}	0.35 ± 0.00^{b}	17.27 ± 0.07^{b}	56.07 ± 0.23^{b}	7.51 ± 0.00^{cd}	0.32 ± 0.00^{bc}	5.05 ± 0.01^{cde}	3.24 ± 0.10^{c}	0.81 ± 0.01^{cd}
F12	0.43 ± 0.03^{b}	0.38 ± 0.02^{a}	19.77 ± 0.18^{a}	55.87 ± 1.00^{b}	8.04 ± 0.29^{ab}	0.39 ± 0.02 a	5.61 ± 0.21^{a}	3.50 ± 0.10^{a}	1.06 ± 0.03^{a}
Maximum	0.47	0.38	18.97	58.20	8.15	0.39	5.63	3.50	1.07
Minimum	0.21	0.26	12.67	34.78	6.46	0.30	4.83	2.65	0.64
Mean	0.33	0.31	16.48	50.35	7.44	0.34	5.19	3.05	0.84
LSD	0.04	0.03	0.84	1.78	0.51	0.024	0.30	0.19	0.57
CV (%)	6.91	5.03	3.02	2.09	4.06	4.23	3.38	3.70	3.99

Mean followed by the same letter(s) within each column do not differ statistically (p= 0.05).

Treat.: treatment; K: potassium, Na: sodium, CEC: cation exchange capacity, BS: base saturation, AS: available sulfur, Cu: copper, Fe: iron, Mn: manganese, Zn: zinc.

Table 4.3 Comparison of physicho-chemical properties of soils of Mudedende (L_1) and Rwerere (L_2) locations

Treat.	Clay (%)	Silt (%)	Sand (%)	BD(gcm^{-3})	pH	OC (%)	TN (%)	AP (%)	Ca (meq/100g)	Mg (meq/100g)
L_1	18.13 ± 0.01^{b}	14.31 ± 0.09^{b}	67.59 ± 0.10^{a}	1.47 ± 0.07^{b}	6.03 ± 0.05a	4.11 ± 0.11a	0.22 ± 0.006^{a}	7.92 ± 0.18^{a}	6.45 ± 0.28^{a}	1.65 ± 0.12^{a}
L_2	20.31 ± 0.01^{a}	15.99 ± 0.05^{a}	63.70 ± 0.05^{b}	1.61 ± 0.10^{a}	5.92 ± 0.06b	3.71 ± 0.05b	0.20 ± 0.008^{b}	7.68 ± 0.18^{b}	6.22 ± 0.26^{b}	1.58 ± 0.12^{b}
Mean	19.22	15.15	65.64	1.54	5.97	3.91	0.21	7.80	6.33	1.61
LSD	0.02	0.17	0.17	0.01	0.09	0.05	0.006	0.21	0.12	0.05
CV (%)	0.26	2.39	0.54	1.40	3.11	2.51	6.49	5.65	4.13	6.90

Mean followed by the same letter(s) within each column do not differ statistically (p= 0.05).
Treat.: treatment; pH: potential of hydrogen, OC: organic carbon, BD: bulk density, TN: total nitrogen, AP: available phosphorus, Ca: calcium, Mg: magnesium, L_1: location 1 (Mudende), L_2: location 2 (Rwerere).

Table 4.3 Continued

Treat.	K (meq/100g)	Na (meq/100g)	CEC (meq/100g)	BS (%0	S(ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	Zn (ppm)
L_1	0.35 ± 0.02^{a}	0.30 ± 0.01^{a}	15.61 ± 0.50^{b}	54.82 ± 1.24^{a}	7.61 ± 0.10^{a}	0.35 ± 0.01^{a}	5.28 ± 0.06^{a}	3.07 ± 0.01^{a}	0.97 ± 0.02^{a}
L_2	0.33 ± 0.01^{b}	0.31 ± 0.01^{a}	16.48 ± 0.36^{a}	50.35 ± 1.53^{b}	7.44 ± 0.09^{b}	0.34 ± 0.01^{b}	5.19 ± 0.05^{b}	3.05 ± 0.01^{a}	0.84 ± 0.02^{b}
Mean	0.34	0.31	16.04	52.58	7.52	0.35	5.24	3.06	0.90
LSD	0.11	0.007	0.23	0.57	0.14	0.007	0.08	0.06	0.01
CV (%)	7.02	5.07	3.00	230	4.04	4.30	3.27	3.57	3.43

Mean followed by the same letter(s) within each column do not differ statistically (p= 0.05).
Treat.: treatment, K: potassium, Na: sodium, CEC: cation exchange capacity, BS: base saturation, AS: available sulfur, Cu: copper, Fe: iron, Mn: manganese, Zn: zinc, L_1: location 1 (Mudende), L_2: location 2 (Rwerere).

4.1.3 Correlation and factor analysis of soil properties

Relationship between soil reaction (pH), organic carbon and other soil properties

The study revealed that properties like organic carbon (OC) and pH are shapers and more indicative of soil fertility status. This association was depicted by analysis of correlation coefficient associating them with other soil parameters. The magnitude and direction of relationships between soil reaction (pH), organic carbon (OC) and other soil properties are displayed in Table 4.4.

Table 4.4 Relationships between soil reaction (pH), organic carbon and other selected soil properties

Variable	**Soil Organic Carbon (SOC)**		**Soil Reaction (pH)**	
	Mudende (L_1)	**Rwerere (L_2)**	**Mudende (L_1)**	**Rwerere (L_2)**
OC	1.000	1.000	r= 0.751***	r= 0.854***
pH	r= 0.751***	r= 0.854***	1.000	1.000
TN	r= 0.853***	r= 0.866***	r= 0.694***	r= 0.751***
BD	r= -0.746***	r= -0.887***	r= -0.543***	r= -0. 852***
AP	r= 0.716***	r= 0.689***	r= 0.649***	r= 0.592***
AS	r= 0.880** *	r= 0.767***	r= 0.648***	r= 0.710***
Ca	R= 0.802** *	r= 0.827***	r= 0.718***	r= 0.759***
Mg	r= 0.728***	r= 0.806***	r= 0.699***	r= 0.714***
K	r= 0.827***	r= 0.779***	r= 0.699***	r= 0.714***
BS	r= 0.558***	r= 0.707***	r= 0.558***	r= 0.707***
CEC	r= 0.750***	r= 0.773***	r= 0.750***	r= 0.773***
Cu	r= 0.885***	r= 0.855***	r= 0.647***	r= 0.722***
Fe	r= 0.789***	r= 0.809***	r= 0.624***	r= 0.735***
Mn	r= 0.927***	r= 0.66***	r= 0.756***	r= 0.803***
Zn	r= 0.924***	r= 0.922***	r= 0.792***	r= 0.829***

OC: organic carbon, pH: potential of hydrogen, TN: total nitrogen, AP: available phosphorus, AS: available sulfur, Ca: calcium, Mg: magnesium, K: potassium, Na: sodium, CEC: cation exchange capacity, BS: base saturation, Cu: copper, Fe: iron, Mn: manganese, Zn: zinc

Relationship between soil organic carbon and other selected soil properties

Organic carbon displayed a positive association with pH (r= 0.751*** [Mudende] and r= 0.854*** [Rwerere]) and total nitrogen (r= 0.853*** [Mudende] and r= 0.866*** [Rwerere], available P (r= 0.716*** [Mudende] and r= 0.689*** [Rwerere]) and sulphur (r= 0.880*** [Mudende] and r= 0.767*** [Rwerere]). The research results depicted also the existence of a positive relationship between organic carbon and cation bases, CEC and BS [Ca (r= 0.802*** [Mudende] and r= 0.827***[Rwerere]), Mg (r= 0.728*** [Mudende] and r= 0.806***[Rwerere]), K (r= 0.827** *[Mudende] and r= 0.779*** [Rwerere])), CEC (r= 0.828*** [Mudende] and r***= 0.848[Rwerere]) and BS (r= 0.610*** [Mudende] and r= 0.761*** [Rwerere]]. Moreover, there was also a positive association between organic carbon and extractable micronutrients: Cu (r= 0.885*** [Mudende] and r= 0.855***[Rwerere]), Fe (r= 0.789*** [Mudende] and r= 0.809***[Rwerere]), Mn (r= 0.927*** [Mudende] and r= 0.66***[Rwerere]) and Zn (r= 0.924*** [Mudende] and r= 0.922***[Rwerere]).]). On the contrary, organic carbon showed a negative association with soil bulk density (r= -0.746*** [Mudende] and r= -0.887** *[Rwerere]).

Relationship between soil reaction (pH) and other selected soil properties

Soil pH displayed a positive relationship with soil OC content (r= 0.751*** [Mudende] and r= 0.854*** [Rwerere]) and TN (r= 0.694*** [Mudende] and r= 0.751*** [Rwerere]), and a negative association with soil bulk density (r= -0.543*** [Mudende] and r= -0. 852*** [Rwerere]). In addition, pH exhibited a positive association with available P (r= 0.649*** [Mudende] and r= 0.592*** [Rwerere]) and Sulphur (r= 0.648*** [L_1] and r= 0.710*** [L_2]). There was also a positive association between pH, exchangeable bases [Ca (r= 0.718** [Mudende] and r= 0.759***[Rwerere]), Mg (r= 0.699*** [Mudende] and r= 0.714***[Rwerere]) and K(r= 0.609*** [Mudende] and r= 0.744***[Rwerere])]; bases saturation (r= 0.558*** [Mudende] and r= 0.707***[Rwerere]) and CEC (r= 0.750*** [Mudende] and r= 0.773*** [Rwerere] (Table 4.4).Moreover, there was a positive relationship between pH and extractable micronutrients: Cu (r= 0.647*** [Mudende] and r= 0.722*** [Rwerere]), Fe (r= 0.624*** [Mudende] and r= 0.735*** [Rwerere]), Mn (r= 0.756*** [Mudende] and r= 0.803*** [Rwerere]) and Zn (r= 0.792*** [Mudende] and r= 0.829*** [Rwerere]). On the contrary, soil pH was negatively associated with bulk density.

Factor analysis for correlated soil chemical attributes

Data pertaining to rotated factor loadings are displayed in Table 4.5 whereas data concerning factor loading plot are showed in Figures 4.1 and 4.2. Factor analysis extracted two factors which explained 85.2 % [Mudende] and 83.9 % [Rwerere] of total variance. The first factor accounted for 47.7% [Mudende] and 45.3% [Rwerere] of the total variance. It depicted strong positive loadings with respect to OC (0.81), TN (0.78), S (0.92), Cu (0.87), Fe (0.93) and Zn (0.76); and moderate positive loadings with regard to pH (0.54), K (0.62) and Mn (0.75) at Mudende location (L_1) whereas it was characterized by strong positive loadings with regard to OC (0.78), TN (0.76), Cu (0.90) and Zn (0.90); and moderate positive loadings with respect to pH (0.69), K (0.57), S (0.75), Fe (0.73) and Mn (0.69) at Rwerere location (L_2). The second factor accounted for 37.5% [Mudende] and 38.6% [Rwerere] of the total variance, and had strong positive loadings in AP (0.78), Ca (0.86), Mg (0.87), and BS (0.94) at Mudende location while depicted strong positive loadings in Ca (0.87), Mg (0.89) and BS (0.92); and moderate loading in CEC (0.73) and available P (0.57) at Rwerere location.

Table 4.5 Rotated factor loadings of chemical properties of soils of Mudende [L_1] and Rwerere [L_2] locations

	Mudende [L_1]		Rwerere [L_2]	
Variable	**Factor 1**	**Factor 2**	**Factor 1**	**Factor 2**
pH	**0.54**	0.51	**0.69**	0.48
OC	**0.81**	0.45	**0.78**	0.51
TN	**0.78**	0.40	**0.76**	0.45
AP	0.47	**0.78**	0.50	**0.57**
Ca	0.50	**0.86**	0.49	**0.87**
Mg	0.45	**0.87**	0.44	**0.89**
K	**0.62**	0.35	**0.57**	0.54
CEC	0.61	**0.76**	0.59	**0.73**
BS	0.23	**0.94**	0.37	**0.92**
S	**0.92**	0.32	**0.75**	0.47
Cu	**0.87**	0.40	**0.90**	0.33
Fe	**0.93**	0.31	**0.73**	0.58
Mn	**0.75**	0.55	**0.69**	0.56
Zn	**0.76**	0.50	**0.90**	0.42
PCA Variance (%)	47.7	37.5	45.3	38.6
Cumulative Variance (%)		85.2		83.9

OC: organic carbon, pH: potential of hydrogen, TN: total nitrogen, AP: available phosphorus, AS: available sulfur, Ca: calcium, Mg: magnesium, K: potassium, Na: sodium, CEC: cation exchange capacity, BS: base saturation, Cu: copper, Fe: iron, Mn: manganese, Zn: zinc.

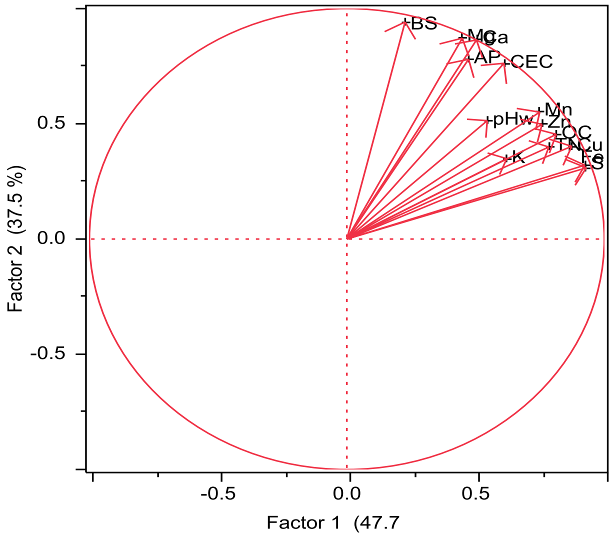


Figure 4.1 Factor loading plot of Mudende (L_1) soil chemical properties

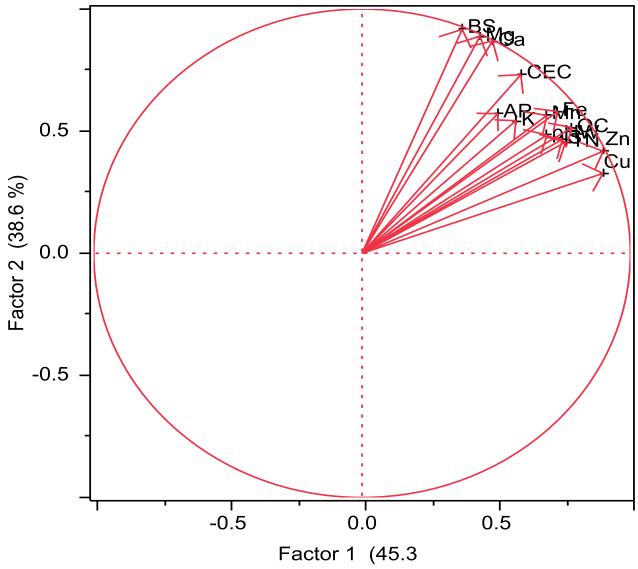


Figure 4.2 Factor loading plot of Rwerere (L_2) soil chemical properties

4.2 Effects of season, Nitrogen, Phosphorus and Potassium on potato growth attributes

4.2.1 Main effect of season, Nitrogen, Phosphorus and Potassium on potato growth attributes in each location

Data related to analysis of variance for growth traits for Mudende location and Rwerere location are presented in Tables 4.6 and 4.7, respectively. The two seasonal results showed similar response patterns with regard to main effect of N, P, and K on potato growth traits. In general, stem height and leaf area index increased with the increasing of nutrient quantity and advancement of crop growth period.

The analysis of variance revealed that the main effects of season, N, P and K fertilizer rates were significant ($p < 0.05$) on stem height and leaf area index (Appendices 3 and 6) whereas they were not significant ($p > 0.05$) on number of main stems per plant, at both locations. Season 2, N_{100}, P_{100} and K_{50} constantly recorded higher values for all growth traits on which the effects of factors under study were significant. Stem height and leaf area index increased over time, higher values were recorded 70 days after emergence (70 DAE) stage. Highest stem height [(52.47 ± 1.38) cm [Mudende] and (46.90 ± 1.20) cm [Rwerere])] and leaf area index (4.24 ± 0.17 [Mudende] and 3.74 ± 0.17 [Rwerere]) were recorded with season 2 (S_2) at both locations. However, effects of season on number of main stems per plant were not significant.

Amongst N treatments, highest stem height [(61.54 ± 1.47) cm [Mudende] and (53.99 ± 1.29) cm [Rwerere])] and leaf area index (5.38 ± 0.14 [Mudende] and 4.95 ± 0.13 [Rwerere]) were observed with application of N_{100} at both locations. Compared with unfertilized control (N_0), N_{100} increased stem height by 51.39% (Mudende) and 33.90% (Rwerere); leaf area index by 113.49% (Mudende) and 132.39% (Rwrere). With P application, highest stem height [(56.46± 1.70) cm [Mudende] and (49.54 ± 1.48) cm [Rwerere]) and leaf area index (4.58± 0.21 [Mudende] and 4.17 ± 0.20 [Rwerere]) were observed with application of P_{100} at both locations. Compared with its corresponding non-fertilized control, application of P_{100} increased stem height by 27.05% (Mudende) and 26.89% (Rwerere); leaf area by 38.37% (Mudende) and 43.79% (Rwerere). Concerning K application, highest stem height [(53.82 ± 1.41) cm [Mudende] and (47.24 ± 1.23) cm [Rwerere]) and leaf area index (4.28 ± 0.18 [Mudende] and 3.87 ± 0.17 [Rwerere]) were observed with application of K_{50}at both locations. Application of K_{50} increased stem height by 8.16% (Mudende) and 8.07% (Rwerere); leaf area index by 8.63% (Mudende) and 9.63% (Rwerere) compared with its unfertilized control. Contrariwise, effect N, P and K application did not significantly ($p > 0.05$) affect the number of main stems per plant at both locations.

Table 4.6 Effect of season, Nitrogen, Phosphorus and Potassium on growth attributes (Mudende location)

		SH30 DAE	SH50 DAE	SH70 DAE	SN15 DAE	SN30 DAE	LAI30 DAE	LAI50 DAE	LAI70 DAE
N	0	31.28 ± 0.42[c]	38.58 ± 0.52[c]	40.65 ± 0.53[c]	4.56 ± 0.03	4.55 ± 0.03	1.31 ± 0.06[c]	2.49 ± 0.12[c]	2.52 ± 0.11[c]
	50	41.19 ± 0.77[b]	50.87 ± 0.96[b]	53.19 ± 0.98[b]	4.56 ± 0.03	4.58 ± 0.03	2.31 ± 0.07[b]	4.35 ± 0.13[b]	4.43 ± 0.13[b]
	100	47.78 ± 1.16[a]	59.06 ± 1.44[a]	61.54 ± 1.47[a]	4.56 ± 0.03	4.58 ± 0.03	2.80 ± 0 .07[a]	5.27 ± 0.14[a]	5.38 ±0.14[a]
LSD		0.70	0.87	0.89	0.10	0.10	0.01	0.03	0.03
P	0	34.27± 0.67[c]	42.29 ± 0.83[c]	44.44 ± 0.84[c]	4.56 ± 0.03	4.55 ± 0.05	1.72 ± 0.09[c]	3.25 ± 0.18[c]	3.31 ±0.18[c]
	50	42.21 ± 1.31[b]	52.14 ± 1.62[b]	54.48 ± 1.65[b]	4.56 ± 0.03	4.58 ± 0.03	2.31 ± 0.11[b]	4.35 ± 0.20[b]	4.44 ± 0.20[b]
	100	43.77 ± 1.34[a]	54.08 ± 1.66[a]	56.46 ± 1.70[a]	4.56 ± 0.03	4.58 ± 0.03	2.39 ± 0.11[a]	4.49 ± 0.21[a]	4.58 ± 0.21[a]
LSD		0.70	0.87	0.89	0.10	0.10	0.01	0.03	0.03
K	0	38.48 ± 0.95[b]	47.51 ± 1.18[b]	49.76 ± 1.21[b]	4.56 ± 0.02	4.58 ± 0.02	2.05 ± 0.09[b]	3.87 ± 0.17[b]	3.94 ± 0.17[b]
	50	41.69 ±1.12[a]	51.49 ± 1.39[a]	53.82 ± 1.41[a]	4.56 ± 0.02	4.56 ± 0.03	2.23 ± 0.09[a]	4.20 ± 0.17[a]	4.28 ± 0.18[a]
LSD		0.57	0.71	0.73	0.08	0.08	0.01	0.02	0.02
Season	1	39.55 ± 1.01[b]	48.84 ± 1.26[b]	51.11 ± 1.28[b]	4.56 ± 0.02	4.56 ± 0.02	2.07± 0.09[b]	3.94 ± 0.17[b]	3.98 ± 0.17[b]
	2	40.62 ± 1.09[a]	50.17 ± 1.35[a]	52.47 ± 1.38[a]	4.57 ± 0.02	4.58 ± 0.03	2.20 ± 0.09[a]	4.13 ± 0.17a	4.24 ± 0.17[a]
LSD		0.57	0.71	0.73	0.08	0.08	0.01	0.02	0.02
Mean		40.08	49.50	51.79	4.56	4.57	2.14	4.03	4.11
CV		4.34	4.36	4.25	5.18	5.40	1.59	1.82	1.58

Mean followed by the same letter(s) within each column do not differ statistically (p= 0.05).

SH: stem height [cm], DAE: days after emergence, SN: number of main stems per plant, LAI: leaf area index.

Table 4.7 Effect of season, Nitrogen, Phosphorus and Potassium on growth attributes (Rwerere location)

		SH30 DAE	SH50 DAE	SH70 DAE	SN15 DAE	SN30 DAE	LAI30 DAE	LAI50 DAE	LAI70 DAE
N	0	27.40 ± 0.36 [c]	33.76 ± 0.45 [c]	35.73 ± 0.45 [c]	4.56 ± 0.03	4.56 ± 0.03	1.07 ± 0.05 [c]	2.10 ± 0.10 [c]	2.13 ± 0.10 [c]
	50	36.06 ± 0.68 [b]	44.51 ± 0.85 [b]	46.70 ± 0.87 [b]	4.55 ± 0.03	4.57 ± 0.03	2.06 ± 0.06 [b]	3.96± 0.11 [b]	4.01 ± 0.12 [b]
	100	41.82 ± 1.02 [a]	51.66 ± 1.26 [a]	53.99 ± 1.29 [a]	4.55 ± 0.03	4.57 ± 0.04	2.56 ± 0.07 [a]	4.9 ± 0.13 [a]	4.95 ± 0.13 [a]
LSD		0.42	0.52	0.53	0.09	0.11	0.04	0.08	0.08
P	0	30.00 ± 0.57 [c]	37.00 ± 0.70 [c]	39.04 ± 0.72 [c]	4.55 ± 0.03	4.56 ± 0.03	1.48 ± 0.09 [c]	2.86 ± 0.17 [c]	2.90 ± 0.17 [c]
	50	36.97 ± 1.15 [b]	45.64 ± 1.43 [b]	47.85 ± 1.46 [b]	4.56 ± 0.04	4.57 ± 0.03	2.07 ± 0.10 [b]	3.98 ± 0.19 [b]	4.03 ± 0.20 [b]
	100	38.30 ± 1.17 [a]	47.29 ± 1.45 [a]	49.54 ± 1.48 [a]	4.56 ± 0.03	4.56 ± 0.03	2.14 ± 0.11 [a]	4.11 ± 0.20 [a]	4.17 ± 0.20 [a]
LSD		0.42	0.52	0.53	0.09	0.11	0.04	0.08	0.08
K	0	33.70 ± 0.84 [b]	41.58 ± 1.04 [b]	43.71 ± 1.06 [b]	4.56 ± 0.03	4.57 ± 0.03	1.81 ± 0.09 [b]	3.48 ± 0.16 [b]	3.53 ± 0.17 [b]
	50	36.49 ± 0.97 [a]	45.04 ± 1.21 [a]	47.24 ± 1.23 [a]	4.56 ± 0.03	4.57 ± 0.03	1.99 ± 0.09 [a]	3.82 ± 0.17 [a]	3.87 ± 0.17 [a]
LSD		0.34	0.42	0.43	0.08	0.09	0.03	0.06	0.06
Season	1	33.96 ± 0.88 [b]	41.91 ± 1.09 [b]	44.05 ± 1.12 [b]	4.54 ± 0.02	4.55 ± 0.03	1.84 ± 0.09 [b]	3.61 ± 0.17 [b]	3.66 ± 0.17 [b]
	2	3.2 2 ± 0.95 [a]	44.71 ± 1.17 [a]	46.90 ± 1.20 [a]	4.56 ± 0.02	4.58 ± 0.03	1.95 ± 0.09 [a]	3.69 ± 0.17 [a]	3.74 ± 0.17 [a]
LSD		0.34	0.42	0.43	0.08	0.09	0.03	0.06	0.07
Mean		35.09	43.31	45.47	4.55	4.56	1.89	3.65	3.70
CV		2.94	2.95	2.87	5.11	5.82	5.40	5.42	5.42

Mean followed by the same letter(s) within each column do not differ statistically (p= 0.05).

SH: stem height [cm], DAE: days after emergence, SN: number of main stems per plant, LAI: leaf area index.

4.2.2 Interaction effect of season, Nitrogen, Phosphorus and Potassium on potato growth attributes in each location

Season × N× P× K was found not to significantly ($p > 0.05$) affect growth parameters at both locations. The fertilizer rates performed in similar ways in both seasons across locations. The results of analysis of variance on N× P × K effects on potato growth traits are presented in Tables 4.8 (Mudende) and 4.9 (Rwerere). The analysis revealed that the interaction N× P × K effects were significant ($p < 0.05$) on stem height and leaf area index (Appendices 3 and 6) whereas they were not significant ($p > 0.05$) on number of main stems per plant at both locations. $N_{100}P_{100}K_{50}$ treatment combination produced the highest plant height [(72.49 ± 1.40) cm [Mudende] and (63.60 ± 1.44) cm [Rwerere]] and leaf area index [(6.09 ± 0.25) [Mudende] and (5.67 ± 0.22) [Rwerere]] while $N_0P_0K_0$ produced the lowest plant height and leaf area index. $N_{100}P_{100}K_{50}$ and $N_0P_0K_0$ treatments stood alone in first and last group of treatment performance for both growth traits under which the factor effects were significant, at both locations. Application of $N_{100}P_{100}K_{50}$ combination led to an increase of 98.11% (Mudende) and 97.20% (Rwerere) in stem height; and 254.07% (Mudende) and 329.54% (Rwerere) in leaf area compared with the corresponding control ($N_0P_0K_0$). In addition, application of $N_{100}P_{100}K_{50}$ combination led to an increase of 22.35% (Mudende) and 21.14% (Rwrere) in stem height; and 21.24% (Mudende) and 26% (Rwrere) in leaf area compared with $N_{50}P_{50}K_{50}$.

Table 4.8 Interaction effect of Nitrogen, Phosphorus and Potassium on growth attributes (Mudende location)

Treat.	SH30 DAE	SE50 DAE	SH70 DAE	SN15 DAE	SN30 DAE	LAI30 DAE	LAI50 DAE	LAI70 DAE
$N_{100}P_{100}K_{50}$	56.44 ± 1.11^{a}	69.79 ± 1.37^{a}	72.49 ± 1.40^{a}	4.57 ± 0.01	4.57 ± 0.05	3.17 ± 0.13^{a}	5.97 ± 0.27^{a}	6.09 ± 0.25^{a}
$N_{100}P_{50}K_{50}$	54.47 ± 1.28^{b}	67.35 ± 1.59^{b}	70.00 ± 1.62^{b}	4.56 ± 0 .09	4.56 ± 0.10	3.12 ± 0.13^{b}	5.88 ± 0.26^{b}	6.00 ± 0.24^{b}
$N_{100}P_{100}K_{0}$	50.89 ± 1.01^{c}	62.91 ± 1.25^{c}	65.47 ±0 1.28^{c}	4.56 ± 0.09	4.59 ± 0.09	3.05 ± 0.12^{c}	5.74 ± 0.25^{c}	5.86 ± 0.23^{c}
$N_{100}P_{50}K_{0}$	49.23 ± 1.06^{c}	60.84 ± 1.32^{c}	63.36 ± 1.34^{c}	4.56 ± 0.09	4.59 ± 0.09	2.89 ± 0.12^{d}	5.45 ± 0.25^{d}	5.56 ± 0.23^{d}
$N_{50}P_{50}K_{50}$	46.44 ± 1.31d	57.39 ± 1.62^{d}	59.84 ± 1.66^{d}	4.56 ± 0.09	4.56 ± 0.10	2.56 ± 0.11^{f}	4.83 ± 0.23^{f}	4.93 ± 0.21^{f}
$N_{50}P_{100}K_{50}$	45.98 ± 0.91^{d}	56.82 ± 1.13^{d}	59.25 ± 1.15^{d}	4.57 ± 0.01	4.57 ± 0.05	2.65 ± 0.13^{e}	4.99 ± 0.27^{e}	5.09 ± 0.26^{e}
$N_{50}P_{100}K_{0}$	43.78 ± 1.44^{e}	54.09 ± 1.79^{e}	56.47 ± 1.82^{e}	4.56 ± 0.09	4.59± 0.09	2.42 ± 0.11^{g}	4.56 ± 0.23^{g}	4.65 ± 0.21^{g}
$N_{50}P_{50}K_{0}$	38.98 ± 0.69^{f}	48.14 ± 0.86^{f}	50.40 ± 0.88^{f}	4.56 ± 0.09	4.57 ± 0.10	2.37 ± 0.13^{h}	4.47 ± 0.26^{h}	4.56 ± 0.24^{h}
$N_{100}P_{0}K_{50}$	37.93 ± 0.92^{fg}	46.83 ± 1.14^{fg}	49.06 ± 1.16^{fg}	4.56 ± 0.09	4.57 ± 0.09	2.32 ± 0.12^{i}	4.37 ± 0.25^{i}	4.46 ± 0.23^{i}
$N_{100}P_{0}K_{0}$	37.76 ± 1.14^{fg}	46.62 ± 1.42^{fg}	48.85 ± 1.45^{fg}	4.567± 0.01	4.59 ± 0.09	2.23 ± 0.11^{j}	4.20 ± 0.24^{j}	4.28 ± 0.22^{j}
$N_{50}P_{0}K_{50}$	37.09 ± 0.89^{g}	45.79 ± 1.04^{g}	48.01 ± 1.15^{g}	4.56 ± 0.09	4.56 ± 0.10	2.11 ± 0.13^{k}	3.98 ± 0.26^{k}	4.05 ± 0.24^{k}
$N_{50}P0K_{0}$	34.85 ± 0.96^{h}	43.01 ± 1.19^{h}	45.17 ± 1.21^{h}	4.55 ± 0.01	4.62 ± 0.09	1.73 ± 0.13^{l}	3.26 ± 0.27^{l}	3.32 ± 0.25^{l}
$N_{0}P_{100}K_{50}$	33.65 ± 0.95^{h}	41.52 ± 1.18^{h}	43.65 ± 1.21^{h}	4.56 ± 0.01	4.53 ± 0.08	1.58 ± 0.13^{m}	2.99 ± 0.26^{m}	3.04 ± 0.24^{m}
$N_{0}P_{50}K_{50}$	33.27 ± 0.90^{hi}	41.05 ± 1.12^{hi}	43.17 ± 1.14^{i}	4.56 ± 0.09	4.57 ± 0.10	1.47 ± 0.12^{n}	2.78 ± 0.25^{n}	2.82 ± 0.23^{n}
$N_{0}P_{100}K_{0}$	31.88 ± 0.81^{ij}	39.33 ± 1.01^{ij}	41.42 ± 1.03^{ij}	4.56 ± 0.09	4.55 ± 0.01	1.44 ± 0.13^{n}	2.73 ± 0.26^{n}	2.77 ± 0.25^{n}
$N_{0}P_{50}K_{0}$	30.87 ± 0.79^{k}	38.07 ± 0.98^{jk}	40.13 ± 1.00^{jk}	4.56 ± 0.09	4.55 ± 0.01	1.44 ± 0.12^{n}	2.72 ± 0.25^{n}	2.76 ± 0.23^{n}
$N_{0}P_{0}K_{50}$	29.93 ± 0.70^{k}	36.91 ± 0.87^{k}	38.95 ± 0.89^{k}	4.56 ± 0.09	4.57 ± 0.10	1.05 ± 0.13^{o}	2.00 ± 0.26^{o}	2.03 ± 0.24^{o}
$N_{0}P_{0}K_{0}$	28.07 ± 0.62^{l}	34.60 ± 0.76^{l}	36.59 ± 0.78^{l}	4.55 ± 0.01	4.55 ± 0.01	0.89 ± 0.10^{p}	1.70 ± 0.22^{p}	1.72 ± 0.20^{p}
Mean	40.08	49.50	51.79	4.56	4.57	2.14	4.03	4.11
LSD	1.72	2.14	2.18	0.23	0.24	0.03	0.06	0.06
CV	4.34	4.36	4.25	5.18	5.40	1.59	1.82	1.58

Mean followed by the same letter(s) within each column do not differ statistically (p= 0.05).

111 to 332 (Treat/Treatment): $N_1P_1K_1$ to$N_3P_3K_{2;}$ SH: stem height [cm], DAE: days after emergence, SN: number of main stems per plant, LAI: leaf area index.

Table 4.9 Interaction effect of Nitrogen, Phosphorus and Potassium on growth attributes (Rwerere location)

Treat.	SH30 DAE	SH50 DAE	SH70 DAE	SN15 DAE	SN30 DAE	LAI30 DAE	LAI50 DAE	LAI70 DAE
$N_{100}P_{100}K_{50}$	49.41 ± 1.14^{a}	61.07 ± 1.41^{a}	63.60 ± 1.44^{a}	4.57 ± 0.01	4.57 ± 0.05	2.94 ± 0.11^{a}	5.60 ± 0.22^{a}	5.67 ± 0.22^{a}
$N_{100}P_{50}K_{50}$	47.62 ± 0.88^{b}	58.86 ± 1.09^{b}	61.34 ± 1.11^{b}	4.56 ± 0.09	4.56 ± 0.10	2.89 ± 0.11^{ab}	5.52 ± 0.20^{ab}	$5.5\ 9 \pm 0.21^{ab}$
$N_{100}P_{100}K_{0}$	44.57 ± 1.09^{c}	55.07 ± 1.35^{c}	57.47 ± 1.38^{c}	4.56 ± 0.09	4.59 ± 0.09	2.80 ± 0.10^{b}	5.35 ± 0.20^{b}	5.42 ± 0.20^{b}
$N_{100}P_{50}K_{0}$	43.10 ± 1.04^{d}	53.24 ± 1.28^{d}	55.61 ± 1.31^{d}	4.56 ± 0.09	4.59 ± 0.09	2.65 ± 0.11^{c}	5.07 ± 0.21^{c}	5.13 ± 0.21^{c}
$N_{50}P_{50}K_{50}$	40.64 ± 1.07^{e}	50.19 ± 1.33^{e}	52.50 ± 1.36^{e}	4.56 ± 0.09	4.56 ± 0.09	2.32 ± 0.09^{d}	4.44 ± 0.18^{d}	4.50 ± 0.18^{d}
$N_{50}P_{100}K_{50}$	40.29 ± 1.06^{e}	49.75 ± 1.32^{e}	52.05 ± 1.35^{e}	4.57 ± 0.01	4.57 ± 0.05	2.40 ± 0.12^{d}	4.60 ± 0.22^{d}	4.66 ± 0.22^{d}
$N_{50}P_{100}K_{0}$	38.20 ± 0.63^{f}	47.17 ± 0.79^{f}	49.41 ± 0.80^{f}	4.56 ± 0.09	4.59 ± 0.09	2.17 ± 0.09e	4.17 ± 0.17^{e}	4.23 ± 0.17^{e}
$N_{50}P_{50}K_{0}$	34.31 ± 1.53^{g}	42.34 ± 1.90^{g}	44.48 ± 1.94^{g}	4.56 ± 0.09	4.59 ± 0.09	2.13 ± 0.11^{e}	4.09 ± 0.21^{e}	4.14 ± 0.21^{e}
$N_{100}P_{0}K_{50}$	33.22 ± 0.85^{h}	40.98 ± 1.05^{gh}	43.10 ± 1.07^{gh}	4.56 ± 0.09	4.57 ± 0.10	2.08 ± 0.10^{ef}	3.99 ± 0.20^{ef}	4.04 ± 0.20^{ef}
$N_{100}P_{0}K_{0}$	33.00 ± 0.68^{h}	40.71 ± 0.85^{gh}	42.83 ± 0.86^{gh}	4.57 ± 0.01	4.59 ± 0.09	1.98 ± 0.10^{f}	3.81 ± 0.19^{f}	3.86 ± 0.19^{f}
$N_{50}P_{0}K_{50}$	32.45 ± 0.69^{h}	40.03 ± 0.85^{h}	42.13 ± 0.87^{h}	4.56 ± 0.09	4.56 ± 0.10	1.86 ± 0.11^{g}	3.59 ± 0.21^{g}	3.64 ± 0.21^{g}
N_{50}P0K_{0}	30.49 ± 0659^{i}	37.59 ± 0.81^{i}	39.64 ± 0.83^{i}	4.55 ± 0.01	4.62 ± 0.09	1.48 ± 0.11^{h}	2.88 ± 0.22^{h}	2.91 ± 0.22^{h}
$N_{0}P_{100}K_{50}$	29.42 ± 0.55j	36.27 ± 0.69^{i}	38.30 ± 0.70^{i}	4.56 ± 0.01	4.53 ± 0.08	1.34 ± 0.11^{i}	2.61 ± 0.21^{i}	2.64 ± 0.21i
$N_{0}P_{50}K_{50}$	29.10 ± 0.59^{j}	35.88 ± 0.73^{ij}	37.89 ± 0.74^{ij}	4.56 ± 0.09	4.67 ± 0.10	1.24 ± 0.10^{ij}	2.42 ± 0.19^{ij}	2.45 ± 0.19^{ij}
$N_{0}P_{100}K_{0}$	27.92 ± 0.71^{k}	34.41 ± 0.88^{jk}	36.40 ± 0.90^{jk}	4.56 ± 0.09	4.57 ± 0.10	1.20 ± 0.11^{j}	2.35 ± 0.21^{j}	2.38 ± 0.21^{j}
$N_{0}P_{50}K_{0}$	27.06 ± 0.78^{kl}	33.34 ± 0.97^{kl}	35.31 ± 0.99^{kl}	4.56 ± 0.09	4.55 ± 0.01	1.19 ± 010^{j}	2.33 ± 0.19^{j}	2.36 ± 0.20^{j}
$N_{0}P_{0}K_{50}$	26.24 ± 0.70^{l}	32.32 ± 0.87^{l}	34.27 ± 0.88^{l}	4.56 ± 0.09	4.57 ± 0.10	0.81 ± 0.11k	1.62 ± 0.21^{k}	1.64 ± 0.21^{k}
$N_{0}P_{0}K_{0}$	24.64 ± 0.78^{m}	30.34 ± 0.96^{m}	32.25 ± 0.98^{m}	4.55 ± 0.01	4.55 ± 0.01	0.64 ± 0.08^{l}	1.30 ± 0.15^{k}	1.32 ± 0.15^{l}
Mean	35.09	43.31	45.47	4.55	4.56	1.89	3.65	3.70
LSD	1.02	1.27	1.30	0.23	0.26	0.10	0.20	0.20
CV	2.94	2.96	2.87	5.11	5.82	5.40	5.41	5.42

Mean followed by the same letter(s) within each column do not differ statistically ($p= 0.05$).111 to 332 (Treat/Treatment): $N_1P_1K_1$ to$N_3P_3K_{2;}$ SH: stem height [cm], DAE: days after emergence, SN: number of main stems per plant, LAI: leaf area index.

4.2.3 Analysis of variance on pooled basis on the effect of location, season, N, P and K on potato growth attributes

Variances of homogeneity from results of the Bartlett test revealed that the mean squares of individual seasons and locations were homogenous and so combined ANOVA were done. The results of ANOVA on pooled basis for the main effect of location, season, N, P and K are presented in Table 4.10 while N×P×K effects are displayed by Table 4.11.

Main effect of location and season on potato growth based on pooled analysis

In general, stem height and leaf area index increased with advancement of crop growth period. The analysis revealed that the main effects of location and season were significant ($p < 0.05$) on stem height and leaf area index; and non-significant ($p > 0.05$) on number of main stems per plant. Analysis showed in general, that Mudende location and Season 2factor levels remained consistent at first position for all potato growth traits. Compared with Rwerere location, Mudende location increased stem height up to 20.85% and leaf area index up to 12.05%. Season 2 (March –June 2017) led to an increase of 4.90% in stem height and 3.42% in leaf area index versus to season1 (September-December 2016).

Main effect of N, P and K on potato growth based on pooled analysis

In general, stem height and leaf area index increased with the increasing of nutrient rates. The analysis revealed that the main effects of nitrogen, phosphorus and potassium were significant ($p < 0.05$) on stem height and leaf area index; and non-significant ($p > 0.05$) on number of main stems per plant. Analysis showed in general, that N_{100}, P_{100} and K_{50} factor levels remained consistent at first position while N_0, $P_0$and K_0 remained at last position for all potato growth traits on which the effects of factors under study were significant. Amongst N treatments, highest stem height [(57.76 ± 1.12) cm] and leaf area index (5.11 ± 0.10) were observed with application of N_{100}. N_{100} increased stem height by 51.24 % and leaf area index by 121.21% compared with its unfertilized control N_0. With P application, highest stem height [(53.00 ± 1.23) cm] and leaf area index (4.37 ± 0.15) were observed with application of P_{100}. Application of P_{100} increased stem height by 26.95% and leaf area index by 40.97% compared with its corresponding non-fertilized control P_0. Concerning K application, highest stem height [(48.59 ± 0.98) cm] and leaf area index (3.93 ± 0.12) were observed with application of K_{50}. K_{50} increased stem height by 8.13 % and leaf area index by 9.18% compared with its unfertilized control (K_0).

Table 4.10 Main effect of location, season, Nitrogen, Phosphorus and Potassium on potato growth attributes (pooled basis [$L_{1\ \&2}$])

		SH30 DAE	SH50 DAE	SH70 DAE	SN15 DAE	SN30 DAE	LAI30 DAE	LAI50 DAE	LAI70 DAE
N	0	26.30 ± 0.31[c]	33.55 ± 0.45[c]	38.19 ± 0.49[c]	4.56 ± 0.03	4.57 ± 0.03	1.19 ± 0.04[c]	2.28 ± 0.08[c]	2.31 ± 0.08[c]
	50	34.76 ± 0.52[b]	44.34 ± 0.74[b]	49.94 ± 0.80[b]	4.56 ± 0.03	4.57 ± 0.03	2.18 ± 0.05[b]	4.14 ± 0.09[b]	4.18 ± 0.09[b]
	100	40.38 ± 0.75[a]	51.52 ± 1.02[a]	57.76 ± 1.12[a]	4.56 ± 0.03	4.57 ± 0.03	2.68 ± 0.05[a]	5.06 ± 0.10[a]	5.11 ± 0.10[a]
LSD		0.63	0.73	0.55	0.08	0.08	0.02	0.05	0.05
P	0	28.85 ± 0.44[c]	36.80 ± 0.61[c]	41.74 ± 0.67[c]	4.56 ± 0.03	4.57 ± 0.03	1.60 ± 0.06[c]	3.05 ± 0.13[c]	3.10 ± 0.13[c]
	50	35.64 ± 0.83[b]	45.47 ± 1.10[b]	51.17 ± 1.21[b]	4.56 ± 0.03	4.57 ± 0.03	2.19 ± 0.07[b]	4.15 ± 0.14[b]	4.23 ± 0.14[b]
	100	36.96 ± 0.85[a]	47.14 ± 1.13[a]	53.00 ± 1.23[a]	4.56 ± 0.03	4.57 ± 0.03	2.26 ± 0.07[a]	4.29 ± 0.14[a]	4.37 ± 0.15[a]
LSD		0.63	0.73	0.80	0.08	0.08	0.02	0.05	0.05
K	0	32.45 ± 0.60[b]	41.40 ± 0.81[b]	46.74 ± 0.88[b]	4.56 ± 0.02	4.58 ± 0.02	1.93 ± 0.06[b]	3.66 ± 0.12[b]	3.70 ± 0.12[b]
	50	35.18 ± 0.70[a]	44.88 ± 0.93[a]	50.53 ± 1.02[a]	4.56 ± 0.02	4.57 ± 0.02	2.11 ± 0.06[a]	4.00 ± 0.12[a]	4.04 ± 0.12[a]
LSD		0.51	0.60	0.45	0.07	0.07	0.02	0.04	0.04
Location	1	36.09 ± 0.68[a]	47.21 ± 0.89[a]	51.93 ± 0.97a	4.56 ± 0.02	4.58 ± 0.02	2.14 ± 0.06[a]	4.03 ± 0.12[a]	4.09 ± 0.12[a]
	2	31.54 ± 0.59[b]	39.07 ± 0.73[b]	42.97 ± 0.81[b]	4.56 ± 0.02	4.57 ± 0.02	1.89 ± 0.06[b]	3.63 ± 0.12[b]	3.65 ± 0.12[b]
LSD		0.51	0.60	0.45	0.07	0.07	0.02	0.04	0.04
Season	1	33.06 ± 0.65[b]	42.10 ± 0.87[b]	46.32 ± 0.96[b]	4.55 ± 0.02	4.56 ± 0.02	1.96 ± 0.06[b]	3.77 ± 0.12[b]	3.80 ± 0.12[b]
	2	34.57 ± 0.68[a]	44.17 ± 0.88[a]	48.59 ± 0.98[a]	4.57 ± 0.02	4.58 ± 0.02	2.08 ± 0.06[a]	3.89 ± 0.12[a]	3.93 ± 0.12[a]
Mean		**33.82**	**43.14**	**47.46**	**4.56**	**4.57**	**2.02**	**3.82**	**3.88**
CV		**6.51**	**5.95**	**4.10**	**6.29**	**6.29**	**6.75**	**4.40**	**4.92**

Mean followed by the same letter(s) within each column do not differ statistically (p= 0.05).

SH: stem height [cm], DAE: days after emergence, SN: number of main stems per plant, LAI: leaf area index.

Interaction effect of location, season, N, P and K on potato growth based on pooled analysis

The interaction effects of Location × Season × N× P× K, Location × N× P× K and Season × N× P× K did not significantly ($p > 0.05$) affect growth parameters (stem height, leaf area index and number of main stems per plant) at both locations. The fertilizer rates performed in similar ways at both locations and in both seasons across locations; fertilizer levels having high values in one location or one season within a given location also recorded high values at the other location or in other season and vice versa.

The effects of N × P × K interaction on stem height and leaf area index were significant ($p < 0.05$), while the interaction effects on number of main stems per potato plant were not responsive ($p > 0.05$) to the N × P × K interaction. $N_{100}P_{100}K_{50}$ and$N_0P_0K_0$treatments recorded the highest and lowest values, respectively for all traits on which the effects were significant. $N_{100}P_{100}K_{50}$ came consistently at first position with tallest stem height [(68.04 ± 1.89) cm] and largest leaf area index (5.85 ± 0.18).Application of $N_{100}P_{100}K_{50}$combination led to an increase of 97.67% in stem height and 287.42% in leaf area compared with the corresponding unfertilized control ($N_0P_0K_0$). Moreover, application of $N_{100}P_{100}K_{50}$ combination led to an increase of 21.13% in stem height and 25.0% in leaf area compared with $N_{50}P_{50}K_{50}$.

Table 4.11 Interaction effect of Nitrogen, Phosphorus and Potassium on potato growth attributes (pooled basis [$L_{1\ \&\ 2}$])

Treat.	SH30 DAE	SH50 DAE	SH70 DAE	SN15 DAE	SN30 DAE	LAI30 DAE	LAI50 DAE	LAI70 DAE
$N_{100}P_{100}K_{50}$	47.78 ± 1.08[a]	60.96 ± 1.75[a]	68.04 ± 1.89[a]	4.56 ± 0.06	4.57 ± 0.06	2.92 ± 0.10[a]	5.79 ± 0.17[a]	5.85 ± 0.18[a]
$N_{100}P_{50}K_{50}$	46.07 ± 1.06[b]	58.76 ± 1.67[b]	64.65 ± 1.80[b]	4.56 ± 0.06	4.57 ± 0.07	2.89 ± 0.10[a]	5.70 ± 0.16[a]	5.76 ± 0.17[a]
$N_{100}P_{100}K_0$	43.05 ± 0.99[c]	54.93 ± 1.59[c]	60.43 ± 1.72[c]	4.56 ± 0.06	4.57 ± 0.06	2.83 ± 0.10[a]	5.55 ± 0.16[b]	5.60 ± 0.17[b]
$N_{100}P_{50}K_0$	41.62 ± 0.97[c]	53.10 ± 1.55[d]	58.42 ± 1.67[d]	4.56 ± 0.06	4.58 ± 0.06	2.69 ± 0.10[b]	5.26 ± 0.16[c]	5.31 ± 0.17[c]
$N_{50}P_{50}K_{50}$	39.24 ± 1.01[d]	50.05 ± 1.55[e]	55.06 ± 1.66[e]	4.56 ± 0.06	4.57 ± 0.06	2.40 ± 0.09[c]	4.63 ± 0.14[e]	4.68 ± 0.15[e]
$N_{50}P_{100}K_{50}$	38.86 ± 0.91[d]	49.59 ± 1.47e	54.56 ± 1.59[e]	4.56 ± 0.06	4.56 ± 0.06	2.48 ± 0.10[c]	4.79 ± 0.17[d]	4.85 ± 0.18[d]
$N_{50}P_{100}K_0$	36.91 ± 0.95[e]	47.05 ± 1.38[f]	51.77 ± 1.49f	4.56 ± 0.06	4.58 ± 0.06	2.27 ± 0.09[d]	4.35 ± 0.14[f]	4.41 ± 0.15[f]
$N_{50}P_{50}K_0$	32.96 ± 0.92[f]	42.10 ± 1.43[g]	46.32 ± 1.63[g]	4.56 ± 0.06	4.58 ± 0.06	2.23 ± 0.09[d]	4.27 ± 0.17[fg]	4.32 ± 0.17[fg]
$N_{100}P_0K_{50}$	31.98 ± 0.78[fg]	40.80 ± 1.22[gh]	44.88 ± 1.31[h]	4.56 ± 0.06	4.57 ± 0.07	2.19 ± 0.09[de]	4.17 ± 0.16[g]	4.22 ± 0.16[g]
$N_{100}P_0K_0$	31.81 ± 0.81[fg]	40.55 ± 1.20[gh]	44.62 ± 1.29[h]	4.56 ± 0.06	4.58 ± 0.06	2.10 ± 0.09[e]	3.99 ± 0.15[h]	4.05 ± 0.16[h]
$N_{50}P_0K_{50}$	31.25 ± 0.76[g]	39.85 ± 1.16[h]	43.85 ± 1.25[h]	4.56 ± 0.06	4.57± 0.06	2.00 ± 0.09[f]	3.77 ± 0.17[i]	3.82 ± 0.17[i]
$N_{50}P0K_0$	29.34 ± 0.72[h]	37.41 ± 1.10[i]	41.16 ± 1.10i	4.56 ± 0.06	4.58 ± 0.06	1.67 ± 0.09[g]	3.04 ± 0.17[j]	3.10 ± 0.18[j]
$N_0P_{100}K_{50}$	28.31 ± 0.70[hi]	36.09 ± 1.04[i]	39.71 ± 1.12[j]	4.56 ± 0.06	4.57 ± 0.06	1.54±0.09h	2.77 ± 0.17[k]	2.82 ± 0.17[k]
$N_0P_{50}K_{50}$	27.99 ± 0.68[hi]	35.69 ± 1.03[ij]	39.26 ± 1.11[j]	4.66 ± 0.07	4.65 ± 0.07	1.44 ± 0.08[i]	2.57 ± 0.15[l]	2.62 ± 0.16[l]
$N_0P_{100}K_0$	26.82 ± 0.67[ij]	34.21± 1.02jk	37.64 ± 1.10[k]	4.56 ± 0.06	4.58 ± 0.06	1.41 ± 0.09[i]	2.51 ± 0.16[l]	2.56 ± 0.17[l]
$N_0P_{50}K_0$	25.97 ± 0.66[jk]	33.12 ± 1.02[kl]	36.44 ± 1.10[kl]	4.56 ± 0.06	4.58 ± 0.06	1.41 ± 0.08[i]	2.49 ± 0.16[l]	2.55 ± 0.16[l]
$N_0P_0K_{50}$	25.17 ± 0.62[k]	32.10 ± 0.95[l]	35.32 ± 1.03[l]	4.56 ± 0.06	4.57 ± 0.07	1.07 ± 0.08[j]	1.77 ± 0.17[m]	1.82 ± 0.17[m]
$N_0P_0K_0$	23.59 ± 0.59[l]	30.10 ± 0.99[m]	34.42 ± 1.01[m]	4.56 ± 0.06	4.58 ± 0.06	0.90 ± 0.07[k]	1.46 ± 0.13[n]	1.51 ± 0.14[n]
Mean	33.82	43.14	47.46	4.56	4.57	2.02	3.82	3.89
LSD	1.53	1.79	1.36	0.2	0.2	0.10	0.12	0.13
CV	6.51	5.95	4.10	6.29	6.29	6.75	4.40	4.92

Mean followed by the same letter(s) within each column do not differ statistically (p= 0.05).

111 to 332 (Treat/Treatment): $N_1P_1K_1$ to $N_3P_3K_{2;}$ SH: stem height [cm], DAE: days after emergence, SN: number of main stems per plant, LAI: leaf area index.

4.3 Effect of season, Nitrogen, Phosphorus and Potassium on potato tuber yield and yield components

4.3.1 Main effect of season, Nitrogen, Phosphorus and Potassium on tuber yield and yield components in each location

Results on ANOVA for nutrient agronomic efficiency are displayed by Figures 4.3-4.6 while data associated with analysis of variance for other yield and yield component traits for Mudende location and Rwerere location are presented in Tables 4.12 and 4.13, respectively. The analysis of variance revealed that the main effects of season, N, P and K fertilizer rates were significant ($p < 0.05$) on number of tubers per plant (NTP), fresh tuber weight (FTW), small sized tuber yield (STY), medium sized tuber yield (MTY), large (big) sized tuber yield (LTY), marketable tuber yield (MATY), unmarketable tuber yield (UMATY) and total tuber yield (TTY) [Appendices 4 and 7], at both locations. Season 2, N_{100}, P_{100} and K_{50} constantly recorded highest values for all traits at both locations except for small and unmarketable tuber yield traits which followed a reverse trend where higher values were recorded with N_0, P_0 and K_0. However N_{100} and N_{50} did not reveal any significant difference at Mudende location.

Compared with season 1, season 2 increased number of tubers per plant by 3.92% (Mudende) and 4.66% (Rwerere), fresh tuber weight by 1.48% (Mudende) and 5.72% (Rwerere) ; small tuber yield and unmarketable tuber yields by 18% (Mudende) and 10.50% (Rwerere); medium tuber yield by 6.01% (Mudende) and 3.33% (Rwerere); large tuber yield by 6.36% (Mudende) and 16.78% (Rwerere); marketable tuber yield by 6.08% (Mudende) and 8.04% (Rwerere) and total tuber yield by 7.38% (Mudende) and 8.39% (Rwerere).

N_{100} increased number of tubers per plant up to 122.67% (Mudene) and 176.19% (Rwerere); fresh tuber weight up to 124.46% (Mudene) and 175.97% (Rwerere); maketable tuber yield up to 171.12% (Mudende) and 308% (Rwerere); and total tuber yield up to 122.96% (Mudene) and 181.40% (Rwerere) compared with the unfertilized control N_0. Application of P_{100} increased number of tubers per plant by 60.72% (Mudene) and 79.46% (Rwerere); fresh tuber weight by 61.58% (Mudene) and 78.04% (Rwerere); marketable tuber yield up to 77.43% (Mudende) and 110.66% (Rwerere); and total tuber yield by 62.02% (Mudene) and 81.24% (Rwerere) versus to its corresponding unfertilized control P_0.

Table 4.12 Effect of season, nitrogen, phosphorus and potassium on tuber yield and yield components at Mudende (L_1)

		NTP	**FTW**	**STY**	**MTY**	**LTY**	**MATY**	**UMATY**	**TTY**
N	0	3.44 ± 0.08[b]	27.59 ± 0.62[b]	2.65 ± 0.05[a]	5.37 ± 0.18[b]	2.87 ± 0.09[b]	8.24± 0.27[b]	2.65 ± 0.02[a]	10.89 ± 0.26[b]
	50	7.63 ± 0.28[a]	61.64 ± 2.30[a]	1.94 ± 0.06[b]	14.52± 0.63[a]	7.81 ± 0.34[a]	22.32± 0.95[a]	1.94 ± 0.06[b]	24.26 ± 0.90[a]
	100	7.66± 0.30[a]	61.93 ± 2.43[a]	1.94 ± 0.06[b]	14.53 ± 0.65[a]	7.81 ± 0.35[a]	22.34 ± 0.99[a]	1.94 ± 0.06b	24.28 ± 0.95[a]
LSD		0.08	0.64	0.04	0.26	0.20	0.29	0.04	0.26
P	0	4.71 ± 0.25[c]	37.85 ± 2.02[c]	2.41 ± 0.07[a]	8.08 ± 0.55[c]	4.36 ± 0.29[c]	12.45 ± 0.84[c]	2.41 ± 0.07[a]	14.86 ± 0.80[c]
	50	6.45 ± 0.34[b]	52.15 ± 2.75[b]	2.14 ± 0.07[b]	11.95 ± 0.73[b]	6.41 ± 0.40[b]	18.36 ± 1.12[b]	2.14 ± 0.07[b]	20.50 ± 1.07[b]
	100	7.57 ± 0.40[a]	61.16 ± 3.26[a]	1.98 ± 0.07[c]	14.38 ± 0.87[a]	7.72 ± 0.47[a]	22.09 ± 1.34[a]	1.98 ± 0.07[c]	24.07 ± 1.29[a]
LSD		0.08	0.64	0.04	0.26	0.20	0.29	0.04	0.26
K	0	5.41 ± 0.27[b]	43.57 ± 2.17[b]	2.31 ± 0.06[a]	9.64 ± 0.58[b]	5.18 ± 0.31[b]	14.82 ± 0.89[b]	2.32± 0.06[a]	17.14 ± 0.85[b]
	50	7.08 ± 0.31[a]	57.20 ± 2.53[a]	2.04 ± 0.06[b]	13.30 ± 0.68[a]	7.14 ± 0.37[a]	20.44 ± 1.04[a]	2.04 ± 0.06[b]	22.49 ± 1.00[a]
LSD		0.06	0.52	0.03	0.21	0.16	0.23	0.03	0.22
Season	1	6.12 ± 0.31[b]	50.02 ± 2.38[b]	2.00 ± 0.06[b]	11.14 ± 0.67[b]	5.97 ± 0.36[b]	17.11 ± 1.02[b]	2.00 ± 0.06[b]	19.11 ± 0.97[b]
	2	6.36 ± 0.30[a]	50.76 ± 2.60[a]	2.36 ± 0.06[a]	11.81 ± 0.67[a]	6.35 ± 0.36[a]	18.15 ± 1.03[a]	2.36± 0.06[a]	20.52 ± 0.98[a]
LSD		0.06	0.52	0.03	0.21	0.16	0.23	0.03	0.22
Mean		6.24	50.39	2.18	11.45	6.16	17.63	2.18	19.78
CV		3.16	3.13	4.38	5.60	7.93	4.01	4.36	3.32

Mean followed by the same letter(s) within each column do not differ statistically (p= 0.05).

NTP: number of tubers per plant, FTW: fresh tuber weight [g], STY: small tuber yield [$t.ha^{-1}$], MTY: medium tuber yield [$t.ha^{-1}$], LTY: large tuber yield [$t.ha^{-1}$], MATY: marketable tuber yield [$t.ha^{-1}$], UMATY: unmarketable tuber yield [$t.ha^{-1}$], TTY: total tuber yield [$t.ha^{-1}$]

Table 4.13 Effect of season, Nitrogen, Phosphorus and Potassium on tuber yield and yield components at Rwerere (L_2)

		NTP	FTW	STY	MTY	LTY	MATY	UMATY	TTY
N	0	2.52 ± 0.08[c]	19.52 ± 0.63[c]	2.80 ± 0.04[a]	2.93 ± 0.16[c]	1.69 ± 0.10[c]	4.62 ± 0.26[c]	2.80 ± 0.04[a]	7.42 ± 0.25[c]
	50	6.33 ± 0.28[b]	49.58 ± 2.22[b]	2.08 ± 0.05[b]	10.74 ± 0.56[b]	6.16 ± 0.33[b]	16.90 ± 0.88[b]	2.09 ± 0.05[b]	18.99 ± 0.85[b]
	100	6.96 ± 0.32[a]	53.87 ± 2.37[a]	2.04± 0.05[c]	11.98 ± 0.63[a]	6.87 ± 0.37[a]	18.85 ± 0.99[a]	2.04 ± 0.05[c]	20.88 ± 0.95[a]
LSD		0.09	0.67	0.04	0.17	0.10	0.27	0.04	0.25
P	0	3.70 ± 0.24[c]	28.82 ± 1.91[c]	2.54 ± 0.06[a]	5.36 ± 0.50[c]	3.08 ± 0.29[c]	8.44 ± 0.79[c]	2.54 ± 0.06[a]	10.98 ± 0.74[c]
	50	5.48 ± 0.34[b]	42.83 ± 2.68[b]	2.27 ± 0.07[b]	8.98 ± 0.69[b]	5.16 ± 0.40[b]	14.14 ± 1.08[b]	2.27 ± 0.07[b]	16.41 ± 1.03[b]
	100	6.64 ± 0.40[a]	51.31 ± 3.08[a]	2.11 ± 0.07[c]	11.30 ± 0.81[a]	6.48 ± 0.47[a]	17.78 ± 1.28[a]	2.12 ± 0.07[c]	19.90 ± 1.22[a]
LSD		0.09	0.68	0.04	0.17	0.10	0.27	0.04	0.25
K	0	4.41 ± 0.26[b]	34.44 ± 2.09[b]	2.44± 0.05[a]	6.80 ± 0.54[b]	3.91 ± 0.31[b]	10.71 ± 0.85[b]	2.44 ± 0.05[a]	13.15 ± 0.80[b]
	50	6.13 ± 0.32[a]	47.54 ± 2.42[a]	2.17 ± 0.06[b]	10.30 ± 0.63[a]	5.91 ± 0.37[a]	16.20 ± 1.00[a]	2.18 ± 0.06[b]	18.38 ± 0.95[a]
LSD		0.07	0.55	0.03	0.14	0.08	0.22	0.03	0.20
Season	1	5.15 ± 0.31[b]	39.85 ± 2.41[b]	2.19 ± 0.06[b]	8.41 ± 0.64[b]	4.53 ± 0.34[b]	12.94 ± 0.98[b]	2.19± 0.06[b]	15.13 ± 0.98[b]
	2	5.39 ± 0.30[a]	42.13 ± 2.35[a]	2.42 ± 0.06[a]	8.69 ± 0.61[a]	5.29 ± 0.37[a]	13.98 ± 0.98[a]	2.42 ± 0.06[a]	16.40 ± 0.93[a]
LSD		0.07	0.55	0.03	0.14	0.08	0.22	0.03	0.20
Mean		5.27	40.99	2.31	8.55	4.97	13.46	2.31	15.76
CV		4.07	4.10	4.19	4.98	4.91	4.97	4.18	3.95

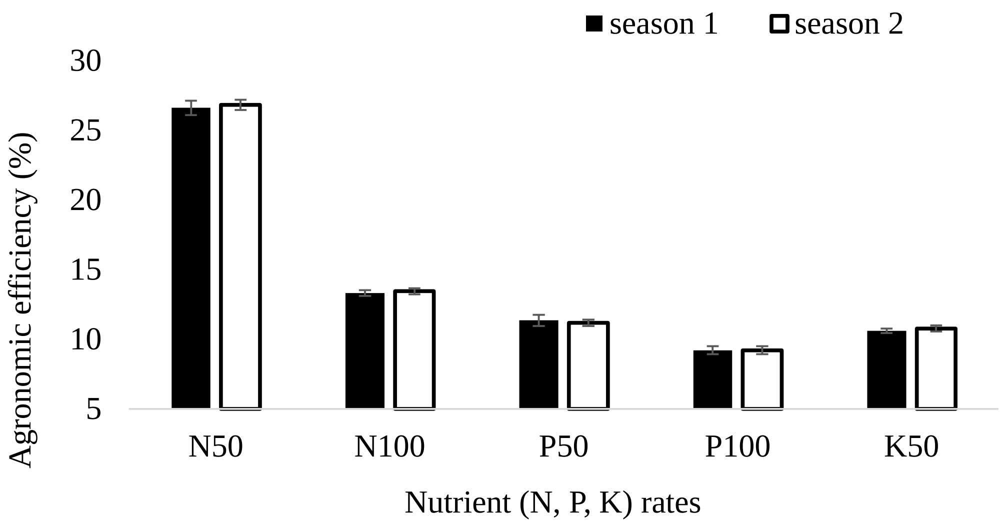
Mean followed by the same letter(s) within each column do not differ statistically (p= 0.05).

NTP: number of tubers per plant, FTW: fresh tuber weight [g], STY: small tuber yield [$t.ha^{-1}$], MTY: medium tuber yield [$t.ha^{-1}$], LTY: large tuber yield [$t.ha^{-1}$], MATY: marketable tuber yield [$t.ha^{-1}$], UMATY: unmarketable tuber yield [$t.ha^{-1}$], TTY: total tuber yield [$t.ha^{-1}$].

Compared with the unfertilized control K_0, application of K_{50} led to an increase of 30.87% (Mudene) and 39.00% (Rwerere) in number of tubers per plant; 31.28% (Mudende) and 38.04% (Rwerere) in fresh tuber weight; 37.92% (Mudende) and 51.26% (Rwerere) in marketable tuber yield; and 31.21% (Mudende) and 39.77% (Rwerere) in total tuber yield. Compared with their unfertilized controls, application of N_{100}, P_{100} and K_{50}, decreased small tuber and unmarketable tuber yields by 26.79% (Mudende) and 27.14% (Rwerere); 17.84% (Mudende) and 16.93% (Rwerere); and 11.69% (Mudende) and 11.06% (Rwerere), respectively.

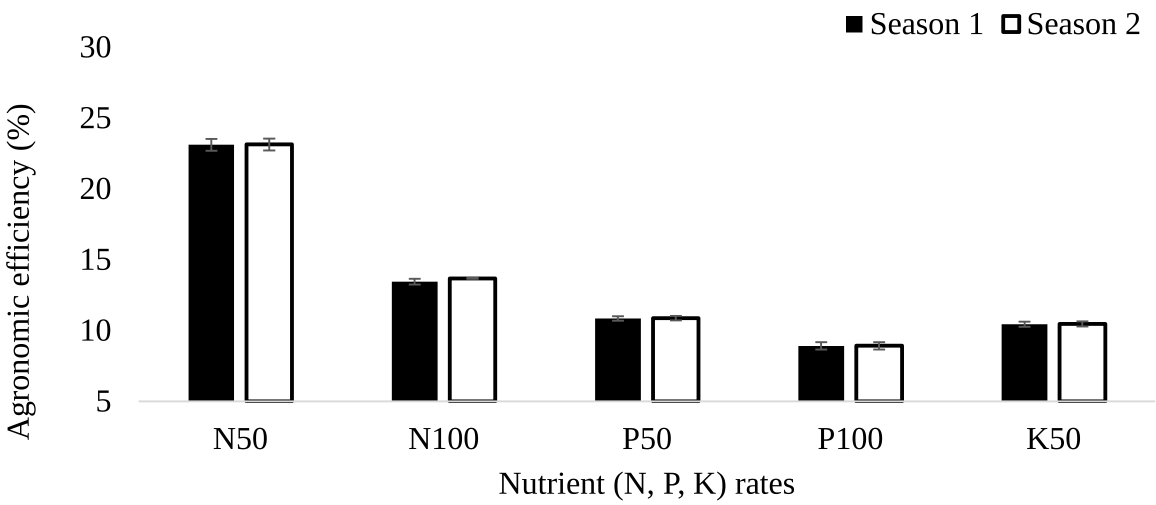
Locational agronomic efficiency (AE) of N, P and K by potato as influenced by season and nutrient rates

Concerning Agronomic Efficiency (AE) of nitrogen and phosphorus, results of single location t-test revealed that AE was significant ($p < 0.05$) at both locations. According to the results of the present study, nutrient AE decreased with increasing nutrient rate, N_{50} and P_{50} recorded highest agronomic efficiency. The results also revealed that effects of season on nutrient agronomic efficiency was not significant ($p > 0.05$) at both locations, however higher AE was recorded with N_{50} (26.84 ± 0.37) during the second season while lower AE was observed with P_{100} (8.91 ± 0.26) during the first season. With regard to results observed across seasons, N_{50} displayed the highest AE [(26.72 ± 0.45)% [Mudende] and (23.13 ± 0.42)% [Rwerere]] whereas P_{100} depicted the lowest AE [(9.22 ± 0.28)% [Mudende] and (8.92 ± 0.26)% [Rwerere]). Compared with N_{50} rate, N_{100} decreased agronomic efficiency by 49.96% [season 1], 49.89% [season 2] and 49.90% [across both seasons] at Mudende location whereas the decrease was 41.80% [season 1], 40.86% [season 2] and 41.76% [across both seasons] at Rwerere location. Application of P_{100} led to a decrease in agronomic efficiency of 18.84% [season 1], 17.60% [season 2] and 18.26% [across both seasons] at Mudende location and 17.88% [season 1], 17.94% [season 2] and 17.86% [across both seasons] at Rwerere location.



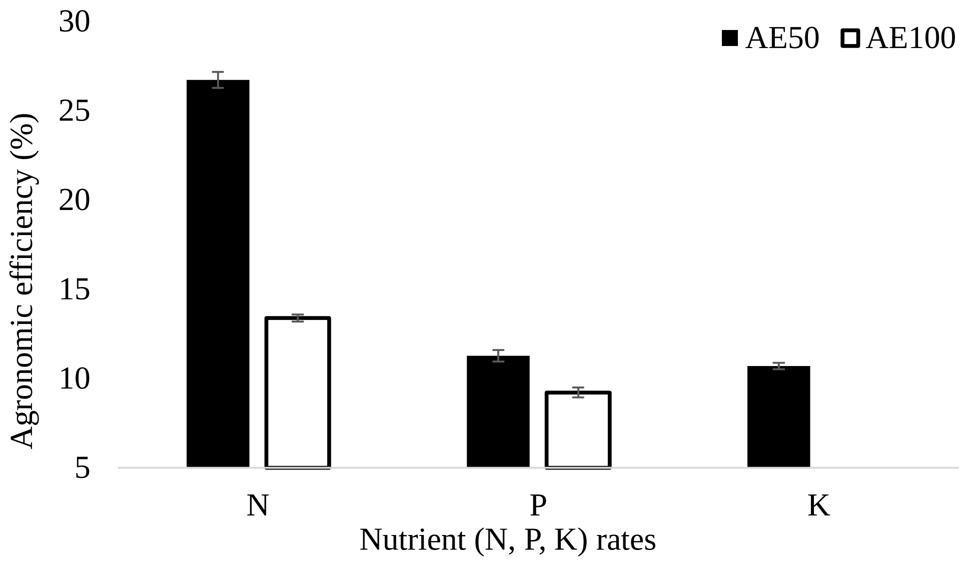
Error bar: ± standard error, significance level: p= 0.05

Figure 4.3 Effect of season on agronomic efficiency- Mudende location (L_1)



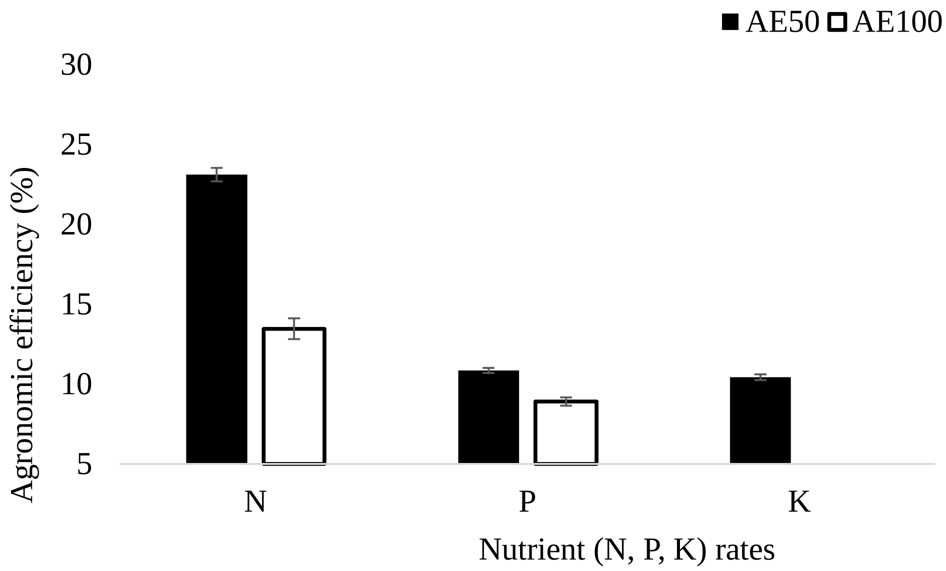
Error bar: ± standard error, significance level: p= 0.05

Figure 4.4 Effect of season on agronomic efficiency- Rwerere location (L_2)



Error bar: ± standard error, significance level: p= 0.05

Figure 4.5 Effects of N, P and K rates on agronomic efficiency- Mudende location



Error bar: ± standard error, significance level: p= 0.05

Figure 4.6 Effects of N, P and K rates on agronomic efficiency- Rwerere location

4.3.2 Interaction effect of season, Nitrogen, Phosphorus and Potassium on tuber yield and yield components

The effect of Season × N× P× K interaction was not significant ($p > 0.05$) on total tuber yield (Appendices 4 and 7) and all yield component traits at both locations. However $S_2N_{100}P_{100}K_{50}$and $S_1N_{50}P_{50}K_{50}$ recorded highest and lowest values, respectively for all traits at both locations except for small and unmarketable yield traits for which the sequence order of treatment combinations was reversed. The results of analysis of variance on nitrogen, phosphorus and potassium interaction effects on potato tuber yield and yield component traits are presented in Tables 4.14 (Mudende) and 4.15 (Rwerere). The analysis revealed that the interaction effects were significant ($p < 0.05$) on all tuber yield and yield component traits.

Application of $N_{100}P_{100}K_{50}$ combination led to an increase of 258.68% (Mudende) and 384.16% (Rwerere) in number of tubers per plant; 276.37% (Mudende) and 393.11% (Rwerere) in fresh tuber weight; 431.96% (Mudende) and 1112.20% (Rwerere) in marketable tuber yield; and 275.32% (Mudende) and 453.96% (Rwerere) in total tuber yield compared with the corresponding unfertilized treatment combination $N_0P_0K_0$. In addition, application of $N_{100}P_{100}K_{50}$ combination led to an increase of 14.02% (Mudende) and 24.74% (Rwerere) in number of tubers per plant; 13.96% (Mudende) and 1.60% (Rwerere) in fresh tuber weight; 13.39% (Mudende) and 27.960% (Rwerere) in marketable tuber yield; and 13.96% (Mudende) and 24.88% (Rwerere) in total tuber yieldcompared with $N_{50}P_{50}K_{50}$. Contrarily, application of $N_{100}P_{100}K_{50}$ decreased small tuber yield and unmarketable tuber yield up to 44.60% (Mudende) and 43.19% (Rwerere) relative to the unfertilized control $N_0P_0K_0$.$N_{100}P_{100}K_{50}$ and $N_0P_0K_0$ treatments stood alone in first and last group of treatment performance for all traits, respectively at both locations except for small and unmarketable tuber yield traits which followed a reverse order. N_{100}, P_{100} and K_{50} proved to bring higher increments to total tuber yield and yield component compared with other factor levels.

Table 4.14 Interaction effect of Nitrogen, Phosphorus and Potassium on tuber yield and yield components at Mudende (L_1)

Treat	NTP	TW	STY	MTY	LTY	MATY	UMATY	TTY
$\mathbf{N_{100}P_{100}K_{50}}$	10.33 ± 0 .11^{a}	83.48 ±1.12^{a}	1.59 ± 0.10^{j}	20.27 ± 0.43^{a}	10.87 ± 0.27^{a}	31.12 ± 0.35^{a}	1.61 ± 0.09^{j}	32.73 ± 0.43^{a}
$\mathbf{N_{100}P_{50}K_{50}}$	9.19 ± 0.11^{c}	74.26 ± 1.04^{c}	1.71 ± 0.10^{hi}	17.79 ± 0.40^{c}	9.55 ± 0.23^{b}	27.34 ± 0.35^{b}	1.71 ± 0.10^{hi}	29.05 ± 0.44^{b}
$\mathbf{N_{100}P_{100}K_{0}}$	8.66 ± 0.13^{d}	70.01 ± 1.15^{d}	1.81 ± 0.10^{g}	16.68 ± 0.43^{e}	8.96 ± 0.27^{c}	25.65 ± 0.38^{c}	1.81 ± 0.10^{g}	27.46 ± 0.48^{d}
$\mathbf{N_{100}P_{50}K_{0}}$	6.68 ± 0.13^{g}	53.99 ± 1.05^{g}	2.10 ± 0.10^{e}	12.41 ± 0.35^{g}	6.67 ± 0.15^{d}	19.08 ± 0.38^{f}	2.17 ± 0.10^{e}	21.18 ± 0.47^{f}
$\mathbf{N_{50}P_{50}K_{50}}$	9.06 ± 0.06^{c}	73.25 ± 0.69c	1.76 ± 0.11^{gh}	17.53 ± 0.29^{cd}	9.44 ± 0.24 $^{b c}$	26.97 ± 0.22^{b}	1.76 ± 0.11^{gh}	28.72 ± 0.32^{bc}
$\mathbf{N_{50}P_{100}K_{50}}$	9.99 ± 0.19^{b}	80.74 ± 1.59^{b}	1.64 ± 0.11^{ij}	19.47 ± 0.41^{b}	10.54 ± 0.43^{a}	30.50 ± 0.66^{a}	1.65 ± 0.11^{ij}	32.16 ± 0.64^{a}
$\mathbf{N_{50}P_{100}K_{0}}$	8.84 ± 0.11^{d}	71.45 ± 1.00^{d}	1.80 ± 0.10^{gh}	17.05 ± 0.35^{de}	9.17b ± 0.24^{c}	26.22 ± 0.35^{c}	1.80 ± 0.10^{gh}	28.02 ± 0.43^{cd}
$\mathbf{N_{50}P_{50}K_{0}}$	6.80 ± 0.07^{fg}	54.98 ± 0.53^{fg}	2.04 ± 0.13^{ef}	12.68 ± 0.24^{fg}	6.85 ± 0.17^{d}	19.53 ± 0.22^{ef}	2.04 ± 0.13^{ef}	21.57 ± 0.32^{f}
$\mathbf{N_{100}P_{0}K_{50}}$	7.06 ± 0.13^{e}	57.06 ± 1.09^{e}	1.96 ± 0.08^{f}	13.28 ± 0.38^{f}	7.14 ± 0.16^{d}	20.42 ± 0.41^{d}	1.96 ± 0.08^{f}	22.38 ± 0.48^{e}
$\mathbf{N_{100}P_{0}K_{0}}$	4.06 ± 0.08^{i}	32.77 ± 0.52^{i}	2.45 ± 0.13^{cd}	6.77 ± 0.18^{h}	3.64 ± 0.10^{ef}	10.41 ± 0.22^{h}	2.45 ± 0.13^{cd}	12.87 ± 0.32^{g}
$\mathbf{N_{50}P_{0}K_{50}}$	6.89 ± 0.12^{ef}	55.65 ± 0.99^{ef}	1.98 ± 0.10^{f}	12.91 ± 0.36^{fg}	6.94 ± 0.17^{d}	19.85 ± 0.38^{de}	2.13 ± 0.10^{ef}	21.83 ± 0.45^{ef}
$\mathbf{N_{50}P_{0}K_{0}}$	4.18 ± 0.09^{hi}	33.76 ± 0.59^{hi}	2.41 ± 0.13^{d}	7.04 ± 0.23^{h}	3.81 ± 0.15^{e}	10.85 ± 0.33^{gh}	1.98 ± 0.13^{f}	13.26 ± 0.35^{gh}
$\mathbf{N_{0}P_{100}K_{50}}$	4.29 ± 0.09^{h}	34.63 ± 0.57^{h}	2.36 ± 0.12^{d}	7.33 ± 0.19^{h}	3.90 ± 0.11^{e}	11.23 ± 0.23^{g}	2.36 ± 0.12d	13.59 ± 0.34^{g}
$\mathbf{N_{0}P_{50}K_{50}}$	3.73 ± 0.09^{j}	30.09 ± 0.60^{j}	2.54 ± 0.12^{c}	6.03 ± 0.18^{i}	3.25 ± 0.09^{f}	9.28 ± 0.23^{i}	2.54 ± 0.12^{c}	11.82 ± 0.34^{h}
$\mathbf{N_{0}P_{100}K_{0}}$	3.30 ± 0.09^{k}	26.68 ± 0.57^{k}	2.65 ± 0.12^{b}	5.08 ± 0.17^{j}	2.75 ± 0.09^{g}	7.83 ± 0.24^{j}	2.65 ± 0.12^{b}	10.48 ± 0.33^{j}
$\mathbf{N_{0}P_{50}K_{0}}$	3.26 ± 0.09^{k}	26.30 ± 0.61^{k}	2.70 ± 0.09^{b}	5.26 ± 0.34^{j}	2.69 ± 0.08^{g}	7.96 ± 0.36^{j}	2.70 ± 0.09^{b}	10.65 ± 0.39^{j}
$\mathbf{N_{0}P_{0}K_{50}}$	3.18 ± 0.09^{k}	25.69 ± 0.62^{k}	2.8 ± 0.10^{a}	4.72 ± 0.19^{j}	2.57 ± 0.08^{g}	7.29 ± 0.25^{j}	2.80 ± 0.10^{a}	10.09 ± 0.34^{j}
$\mathbf{N_{0}P_{0}K_{0}}$	2.88 ± 0.11^{l}	22.18 ± 0.72^{l}	2.87 ± 0.10^{a}	3.78 ± 0.19^{k}	2.07 ± 0.08^{h}	5.85 ± 0.26^{k}	2.87 ± 0.10^{a}	8.72 ± 0.36^{k}
Mean	6.24	50.39	2.18	11.45	6.16	17.63	2.18	19.78
LSD	0.20	1.57	0.09	0.63	0.48	0.70	0.09	0.65
CV	3.16	3.13	4.38	5.59	7.93	4.01	4.36	3.32

Mean followed by the same letter(s) within each column do not differ statistically (p= 0.05).

XYZ (Treat/Treatment): $N_XP_YK_Z$, NTP: number of tubers per plant, FTW: fresh tuber weight [g], STY: small tuber yield [$t.ha^{-1}$], MTY: medium tuber yield [$t.ha^{-1}$], LTY: large tuber yield [$t.ha^{-1}$], MATY: marketable tuber yield [$t.ha^{-1}$], UMATY: unmarketable tuber yield [$t.ha^{-1}$], TTY: total tuber yield [$t.ha^{-1}$].

Table 4.15 Interaction effect of Nitrogen, Phosphorus and Potassium on tuber yield and yield components at Rwerere (L_2)

Treat.	NTP	TW	STY	MTY	LTY	MATY	UMATY	TTY
$N_{100}P_{100}K_{50}$	9.78 ± 0.11^{a}	72.80 ± 1.03^{a}	1.71 ± 0.08^{j}	17.57 ± 0.18^{a}	10.08 ± 0.24^{a}	27.64 ± 0.35^{a}	1.72± 0.08^{j}	29.36 ± 0.41^{a}
$N_{100}P_{50}K_{50}$	8.58 ± 0.12^{b}	67.11 ± 0.97^{b}	1.83 ± 0.08^{hi}	15.20 ± 0.18^{b}	8.72 ± 0.22^{b}	23.91 ± 0.34^{b}	1.83 ± 0.08^{hi}	25.74 ± 0.42^{b}
$N_{100}P_{100}K_{0}$	8.02 ± 0.13^{c}	62.77 ± 1.12^{c}	1.93 ± 0.10^{g}	14.05 ± 0.20^{c}	8.06 ± 0.22^{c}	22.11 ± 0.37^{c}	1.93 ± 0.10^{g}	24.04 ± 0.46^{c}
$N_{100}P_{50}K_{0}$	5.9 3± 0.14^{f}	46.38 ± 1.13^{f}	2.17 ± 0.08^{e}	9.90 ± 0.21^{f}	5.68 ± 0.19^{f}	15.59 ± 0.38^{f}	2.17 ± 0.08^{e}	17.76 ± 0.45^{f}
$N_{50}P_{50}K_{50}$	7.84 ± 0.06^{c}	61.38 ± 0.54^{c}	1.90 ± 0.09^{gh}	13.73 ± 0.11^{c}	7.87 ± 0.20^{c}	21.60 ± 0.26^{c}	1.91 ± 0.09^{gh}	23.51 ± 0.29^{c}
$N_{50}P_{100}K_{50}$	8.73 ± 0.19^{b}	68.32 ± 1.50^{b}	1.79 ± 0.10^{ij}	15.49 ± 0.39^{a}	8.88 ± 0.30^{b}	24.36 ± 0.64^{b}	1.80 ± 0.10^{ij}	26.16 ± 0.61^{b}
$N_{50}P_{100}K_{0}$	7.54 ± 0.12^{d}	59.01 ± 0.96^{d}	1.94 ± 0.08^{g}	13.13 ± 0.18^{d}	7.53 ± 0.21^{d}	20.66 ± 0.34^{d}	1.94 ± 0.08^{g}	22.6 ± 0.41^{d}
$N_{50}P_{50}K_{0}$	5.39 ± 0.07^{g}	42.17 ± 0.65^{g}	2.18 ± 0.12^{e}	8.87 ± 0.07^{g}	5.09 ± 0.15^{g}	13.96 ± 0.21^{g}	2.18 ± 0.12^{e}	16.15 ± 0.30^{g}
$N_{100}P_{0}K_{50}$	6.33 ± 0.14^{e}	49.51 ± 1.15^{e}	2.06 ± 0.06^{f}	10.74 ± 0.23^{e}	6.16 ± 0.21^{e}	16.91 ± 0.40^{e}	2.06 ± 0.06^{f}	18.96 ± 0.46^{e}
$N_{100}P_{0}K_{0}$	3.15 ± 0.08^{i}	24.67 ± 0.71^{i}	2.53 ± 0.11^{d}	4.39 ± 0.10^{i}	2.53 ± 0.11^{i}	6.92 ± 0.21^{i}	2.53 ± 0.11^{d}	9.45 ± 0.30^{i}
$N_{50}P_{0}K_{50}$	5.47 ± 0.13^{g}	42.85 ± 1.06^{g}	2.13 ± 0.09^{ef}	9.08 ± 0.21^{g}	5.21 ± 0.19^{g}	14.29 ± 0.37^{g}	2.13± 0.09^{ef}	16.41 ± 0.43^{g}
$N_{50}P_{0}K_{0}$	3.03 ± 0.07^{i}	23.72 ± 0.60^{i}	2.55 ± 0.12^{d}	4.15 ± 0.15^{i}	2.39 ± 0.13^{i}	6.53 ± 0.27^{i}	2.55 ± 0.12^{d}	9.09 ± 0.26^{i}
$N_{0}P_{100}K_{50}$	3.39 ± 0.09^{h}	26.56 ± 0.76^{h}	2.51 ± 0.11^{d}	4.87 ± 0.11^{h}	2.80 ± 0.12^{h}	7.67 ± 0.23h	2.51 ± 0.11^{d}	10.17 ± 0.31^{h}
$N_{0}P_{50}K_{50}$	2.80 ± 0.09^{j}	21.92 ± 0.78^{j}	2.68 ± 0.11^{c}	3.63 ± 0.12^{j}	2.09 ± 0.11^{j}	5.72 ± 0.22^{j}	2.68 ± 0.11^{c}	8.40 ± 0.31^{j}
$N_{0}P_{100}K_{0}$	2.38 ± 0.07^{k}	18.43 ± 0.76^{k}	2.79 ± 0.11^{b}	2.71 ± 0.13^{k}	1.56 ± 0.11^{k}	4.27 ± 0.24^{k}	2.79 ± 0.11^{b}	7.06 ± 0.30^{k}
$N_{0}P_{50}K_{0}$	2.33 ± 0.07^{k}	18.04 ± 0.78^{k}	2.84 ± 0.08^{b}	2.58 ± 0.14^{k}	1.49 ± 0.11^{k}	4.07 ± 0.25^{k}	2.84 ± 0.08^{b}	6.91 ± 0.31^{k}
$N_{0}P_{0}K_{50}$	2.95 ± 0.07^{k}	17.42 ± 0.79^{k}	2.94 ± 0.08^{a}	2.36 ± 0.14^{k}	1.37 ± 0.11^{k}	3.73 ± 0.25^{k}	2.94 ± 0.08^{a}	6.67 ± 0.31^{k}
$N_{0}P_{0}K_{0}$	2.02 ± 0.10^{l}	14.76 ± 0.88^{l}	3.01 ± 0.09^{a}	1.45 ± 0.15^{l}	0.84 ± 0.10^{l}	2.28 ± 0.26^{l}	3.02 ± 0.09^{a}	5.30 ± 0.33^{l}
Mean	5.27	40.99	2.31	8.55	4.91	13.46	2.31	15.76
LSD	0.21	1.67	0.10	0.42	0.24	0.66	0.09	0.62
CV	4.07	4.10	4.19	4.98	4.97	4.97	4.18	3.95

Mean followed by the same letter(s) within each column do not differ statistically (p= 0.05).
111 to 332 (Treat/Treatment): $N_1P_1K_1$ to$N_3P_3K_2$; NTP: number of tubers per plant, FTW: fresh tuber weight [g], STY: small tuber yield [t.ha^{-1}], MTY: medium tuber yield [t.ha^{-1}], LTY: large tuber yield [t.ha^{-1}], MATY: marketable tuber yield [t.ha^{-1}], UMATY: unmarketable tuber yield [t.ha^{-1}], TTY: total tuber yield [t.ha^{-1}].

4.3.3 Analysis of variance on pooled basis on the effect of location, season, N, P and K on potato yield and yield components

Variances of homogeneity from results of the Bartlett test revealed that the mean squares of individual seasons (within location and across locations) and locations were homogenous and so a combined ANOVA was done. The results of analysis of variance on pooled basis for the main effect of location, season, N, P and K are presented in Table 4.16 while data reflecting effect of nitrogen, phosphorus and potassium interaction on potato yield and yield components are showed in Table 4.17 and results on nutrient agronomic efficiency are displayed by Figures 4.7-4.9.

Main effect of location and season on potato yield and yield components based on pooled analysis

The analysis revealed that the main effects of location and season were significant ($p < 0.05$) on number of tubers per plant, fresh tuber weight (Appendix 9), small tuber yield, medium tuber yield, large (big) tuber yield, marketable tuber yield (Appendix 10), unmarketable tuber yield and total tuber yield. Analysis revealed that Mudende location and season 2 remained consistent at first position for all total tuber yield and yield component traits except for small and unmarketable tuber yield parameters which followed a reverse order. Compared with Rwerere location, Mudende location increased number of tubers per plant up to 18.40%, fresh tuber weight up to 22.93%, marketable tuber yield up to 30.98% and total tuber yield up to 25.51%. However, Mudende location led to a decrease of 5.63% in small and unmarketable tuber yields versus to Rwerere location. On the other hand, season 2 led to an increase of 4.25% in number of tubers per plant, 3.36% in average fresh tuber weight, 6.92% in marketable tuber yield and 7.83% in total tuber yield. Season 2 led to a decrease of 12.55% in small and unmarketable tuber yields compared with season 1.

Main effect of N, P and K on potato yield and yield components based on pooled analysis

The analysis revealed that the main effects N, P and K were significant ($p < 0.05$) on number of tubers per plant, fresh tuber weight, small tuber yield, medium tuber yield, large tuber yield, marketable tuber yield, unmarketable tuber yield and total tuber yield.

Table 4.16 Effect of location, season, N, P and K on tuber yield and its components (on pooled basis [$L_{1\&2}$])

		NTP	TW	STY	MTY	LTY	MATY	UMATY	TTY
N	0	2.98 ± 0.07[c]	23.56 ± 0.60[c]	2.73 ± 0.03[a]	4.15 ± 0.17[c]	2.28 ± 0.09[c]	6.43 ± 0.26[c]	2.73± 0.03[a]	9.16 ± 0.25[c]
	50	6.98 ± 0.21[b]	55.61 ± 1.71[b]	2.01 ± 0.04[b]	12.63 ± 0.46[b]	6.99 ± 0.25[b]	19.61 ± 0.70[b]	2.01 ± 0.04b	21.62 ± 0.67[b]
	100	7.31 ± 0.22[a]	57.90 ± 1.74[a]	1.99 ± 0.04[c]	13.25 ± 0.47[a]	7.34 ± 0.26[a]	20.59 ± 0.72[a]	1.99 ± 0.04[c]	22.58 ± 0.69[a]
LSD		0.06	0.46	0.03	0.16	0.12	0.19	0.01	0.18
P	0	4.20 ± 0.18[c]	33.34 ± 1.46[c]	2.47 ± 0.05[a]	6.72 ± 0.40[c]	3.72 ± 0.22[c]	10.44 ± 0.61[c]	2.47 ± 0.05[a]	12.92 ± 0.58[c]
	50	5.96 ±0.24[b]	47.49 ± 1.97[b]	2.20 ± 0.05[b]	10.47 ± 0.52[b]	5.78 ± 0.29[b]	16.25 ± 0.80[b]	2.21 ± 0.05[b]	18.46 ± 0.77[b]
	100	7.10±0.29[a]	56.24 ± 2.29[a]	2.04 ± 0.05[c]	12.84 ± 0.61[a]	7.10 ± 0.34[a]	19.94 ± 0.95[a]	2.05 ± 0.05[c]	21.99 ± 0.91[a]
LSD		0.06	0.46	0.03	0.16	0.12	0.19	0.03	0.18
K	0	4.91±0.19[b]	39.00 ± 1.55[b]	2.38 ± 0.04[a]	8.22 ± 0.41[b]	4.54 ± 0.23[b]	12.76 ± 0.64[b]	2.38 ± 0.04[a]	15.14 ± 0.61[b]
	50	6.60±0.23[a]	52.37 ± 1.79[a]	2.10 ± 0.04[b]	11.80 ± 0.48[a]	6.53 ± 0.26[a]	18.32 ± 0.74[a]	2.11 ± 0.04[b]	20.43 ± 0.71[a]
Location	1	6.24 ± 0.22[a]	50.39 ± 1.76[a]	2.18 ± 0.04[b]	11.47 ± 0.47[a]	6.16 ± 0.25[a]	17.63 ± 0.72[a]	2.18 ± 0.04[b]	19.78 ± 0.69[a]
	2	5.27 ± 0.22[b]	40.99 ± 1.68[b]	2.31 ± 0.04[a]	8.55 ± 0.44[b]	4.91 ± 0.25[b]	13.46 ± 0.69[b]	2.31 ± 0.04[a]	15.76 ± 0.66[b]
LSD		0.05	0.38	0.02	0.13	0.10	0.16	0.02	0.15
Season	1	5.64 ± 0.22[b]	44.93 ± 1.74[b]	2.09 ± 0.04[b]	9.77 ± 0.47[b]	5.25 ± 0.26[b]	15.02 ± 0.73[b]	2.09 ± 0.04[b]	17.12 ± 0.69[b]
	2	5.88 ± 0.22[a]	46.44 ± 1.78[a]	2.39 ± 0.04[a]	10.25 ± 0.47[a]	5.82 ± 0.26[a]	16.06 ± 0.73[a]	2.39 ± 0.04[a]	18.46 ± 0.69[a]
LSD		0.05	0.38	0.02	0.13	0.10	0.16	0.02	0.15
Mean		5.76	45.69	2.24	10.01	5.53	15.54	2.24	17.79
LSD		0.05	0.38	0.02	0.13	0.10	0.16	0.02	0.15
CV		3.56	3.55	4.27	5.68	7.52	4.40	4.25	3.57

Mean followed by the same letter(s) within each column do not differ statistically (p= 0.05).

NTP: number of tubers per plant, FTW: fresh tuber weight [g], STY: small tuber yield [$t.ha^{-1}$], MTY: medium tuber yield [$t.ha^{-1}$], LTY: large tuber yield [$t.ha^{-1}$], MATY: marketable tuber yield [$t.ha^{-1}$], UMATY: unmarketable tuber yield [$t.ha^{-1}$], TTY: total tuber yield [$t.ha^{-1}$].

Analysis indicated that N_{100}, P_{100} and K_{50} factor levels remained consistent at first position while N_0, $P_0$and K_0 remained at last position for all total tuber yield and yield component traits on which the study focused except for small and unmarketable tuber yield parameters which followed a reverse order. N_{100} increased number of tubers per plant up to 145.30%, fresh tuber weight up to 145.75%, marketable tuber yield up to 220.22% and total tuber yield up to 146.51% compared with the unfertilized control N_0. In addition, application of P_{100} increased number of tubers per plant by 69.05%, average fresh tuber weight by 68.69%, marketable tuber yield up to 90.99% and total tuber yield by 70.20% versus to its corresponding unfertilized control P_0. Compared with the non-fertilized control K_0, application of K_{50} led to an increase of 34.42% in number of tubers per plant, 34.28% in fresh tuber weight, 43.57% in marketable tuber yield and 34.94% in total tuber yield. Compared with their non-fertilized controls, application of N_{100}, P_{100} and K_{50}, decreased small and unmarketable tuber yields by 27.11%, 17.41% and 17.76%, respectively.

Interaction effect of N, P and K on potato yield and yield components based on pooled analysis

N × P × K interaction influenced significantly ($p < 0.05$) aggregate tuber yield and all yield components parameters (Appendices 9 and 10 for fresh tuber weight and marketable yield). $N_{100}P_{100}K_{50}$ recorded the highest values for potato yield and all yield components except for small tuber yield and unmarketable tuber yield for which the treatment combination recorded the lowest values. Application of $N_{100}P_{100}K_{50}$ combination resulted in an increase of 317.01% in number of tubers per plant, 323.06% in fresh tuber weight, 620.0% in marketable tuber yield and 342.94% in total tuber yield compared with the unfertilized treatment combination $N_0P_0K_0$. Application of $N_{100}P_{100}K_{50}$ combination led to an increase of 18.93% in number of tubers per plant, 16.09% in fresh tuber weight, 21.00% in marketable tuber yield and 18.87% in total tuber yield compared with $N_{50}P_{50}K_{50}$. Contrarily, application of $N_{100}P_{100}K_{50}$ decreased small tuber yield and unmarketable tuber yield up to 43.88% relative to the unfertilized control $N_0P_0K_0$.N_{100}, P_{100} and K_{50} proved to bring higher increments to total tuber yield and yield component compared with other factor levels.

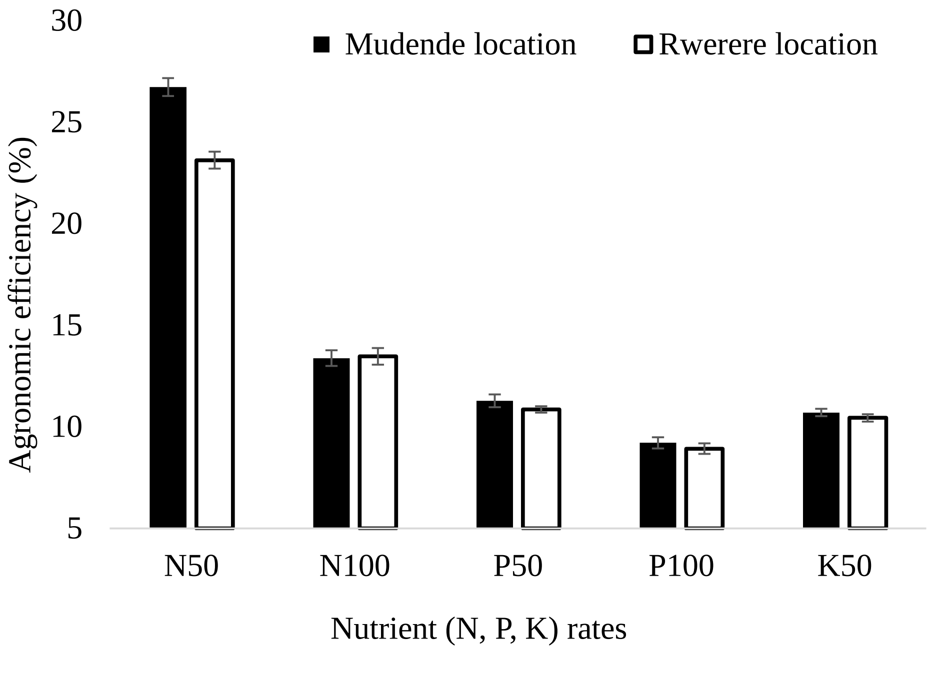
Table 4.17 Interaction effect of N, P and K on tuber yield and yield components (on pooled basis [$L_{1\&2}$])

Treat	NTP	TW	STY	MTY	LTY	MATY	UMATY	TTY
$N_{100}P_{100}K_{50}$	10.05 ± 0.10^{a}	78.14 ± 1.56^{a}	1.65 ± 0.06^{l}	18.92 ± 0.41^{a}	10.47 ± 0.20^{a}	29.38 ± 0.51^{a}	1.66 ± 0.06^{l}	31.05 ± 0.52^{a}
$N_{100}P_{50}K_{50}$	8.88 ± 0.11^{c}	70.69 ± 1.15^{c}	1.77 ± 0.06^{jk}	16.50 ± 0.40^{c}	9.13 ± 0.19^{c}	25.63 ± 0.50^{c}	1.77 ± 0.06^{jk}	27.40 ± 0.52^{c}
$N_{100}P_{100}K_{0}$	8.34 ± 0.12^{d}	66.39 ± 1.21^{d}	1.87 ± 0.07^{i}	15.37 ± 0.40^{de}	8.51 ± 0.19d^{e}	23.88 ± 0.52^{de}	1.87 ± 0.07^{i}	25.75 ± 0.55^{de}
$N_{100}P_{50}K_{0}$	6.30 ± 0.13^{g}	50.19 ± 1.23^{g}	2.14 ± 0.06^{f}	11.16 ± 0.38^{g}	6.18 ± 0.17^{g}	17.34 ± 0.52^{g}	2.14 ± 0.06^{f}	19.47 ± 0.54^{g}
$N_{50}P_{50}K_{50}$	8.45 ± 0.16^{d}	67.31 ± 1.59^{d}	1.83 ± 0.07^{ij}	15.63 ± 0.51^{d}	8.66 ± 0.25^{d}	24.28 ± 0.71^{d}	1.83 ± 0.07^{ij}	26.12 ± 0.71^{d}
$N_{50}P_{100}K_{50}$	9.36 ± 0.21^{b}	74.53 ± 1.92^{b}	1.72 ± 0.08^{k}	17.48 ± 0.58^{b}	9.71 ± 0.33^{b}	27.43 ± 0.91^{b}	1.73 ± 0.07^{kl}	28.91 ± 0.83^{b}
$N_{50}P_{100}K_{0}$	8.19 ± 0.18^{e}	65.23 ± 1.74^{e}	1.87 ± 0.06^{i}	15.09 ± 0.54^{e}	8.35 ± 0.26e	23.44 ± 0.76^{e}	1.87 ± 0.06^{i}	25.31 ± 0.76^{e}
$N_{50}P_{50}K_{0}$	6.10 ± 0.19^{h}	48.58 ± 1.70^{h}	2.11 ± 0.09^{fg}	10.78 ± 0.51^{g}	5.97 ± 0.25^{g}	16.75 ± 0.73^{h}	2.11± 0.09^{fg}	18.86 ± 0.73^{h}
$N_{100}P_{0}K_{50}$	6.69 ± 0.13^{f}	53.29 ± 1.24^{f}	2.01 ± 0.05^{h}	12.01 ± 0.39^{f}	6.65 ± 0.18^{f}	18.66 ± 0.53^{f}	2.01 ± 0.05h	20.67 ± 0.55^{f}
$N_{100}P_{0}K_{0}$	3.61 ± 0.13^{j}	28.72 ± 1.13^{j}	2.49 ± 0.08^{e}	5.58 ± 0.32^{i}	3.09 ± 0.16^{h}	8.67 ± 0.47^{j}	2.49 ± 0.08^{e}	11.16 ± 0.49^{j}
$N_{50}P_{0}K_{50}$	6.18 ± 0.20^{gh}	49.25 ± 1.80^{gh}	2.06 ± 0.07^{gh}	10.99 ± 0.53^{g}	6.07 ± 0.25^{g}	17.07 ± 0.76^{gh}	2.06 ± 0.07^{gh}	19.12 ± 0.76^{gh}
$N_{50}P_{0}K_{0}$	3.61 ± 0.16^{j}	28.74 ± 1.36^{j}	2.48 ± 0.09^{e}	5.59 ± 0.40^{i}	3.10 ± 0.21^{h}	8.69 ± 0.59^{j}	2.48 ± 0.09^{e}	11.17 ± 0.58^{j}
$N_{0}P_{100}K_{50}$	3.84 ± 0.13^{i}	30.59 ± 1.14^{i}	2.44 ± 0.08^{e}	6.10 ± 0.34^{h}	3.35 ± 0.16^{h}	9.45± 0.49^{i}	2.44 ± 0.08^{e}	11.89 ± 0.49^{i}
$N_{0}P_{50}K_{50}$	3.26 ± 0.14^{k}	26.01 ± 1.16^{k}	2.61 ± 0.08^{d}	4.83 ± 0.33^{j}	2.67 ± 0.16^{i}	7.50 ±0.49^{k}	2.61 ± 0.08^{d}	10.11 ± 0.50^{k}
$N_{0}P_{100}K_{0}$	2.84 ± 0.13^{l}	22.55 ± 1.16^{l}	2.72 ± 0.08^{c}	3.90 ± 0.32^{k}	2.16 ± 0.17^{j}	6.05 ± 0.49^{l}	2.72 ± 0.08^{c}	8.77 ± 0.49^{l}
$N_{0}P_{50}K_{0}$	2.79 ± 0.13^{l}	22.17 ± 1.17^{l}	2.77 ± 0.06^{c}	3.92 ± 0.39^{k}	2.09 ± 0.17^{j}	6.01 ± 0.54 ^{l}	2.77 ± 0.06^{c}	8.78 ± 0.54^{l}
$N_{0}P_{0}K_{50}$	2.72 ± 0.13^{l}	21.55 ± 1.17^{l}	2.87 ± 0.07^{b}	3.54 ± 0.33^{k}	1.97 ± 0.17^{j}	5.51 ± 0.49^{m}	2.87 ± 0.07^{b}	8.39 ± 0.49^{l}
$N_{0}P_{0}K_{0}$	2.41 ± 0.14^{m}	18.47 ± 1.10^{m}	2.94 ± 0.07^{a}	2.61 ± 0.32^{l}	1.45 ± 0.17k	4.07 ± 0.49 ^{n}	2.94 ± 0.07^{a}	7.01 ± 0.50^{m}
Mean	5.76	45.69	4.27	10.00	5.53	15.54	2.24	17.77
Lsd	0.14	1.13	0.07	0.40	0.29	0.48	0.07	0.44
CV	3.56	3.55	2.24	5.68	7.52	4.40	4.25	3.58

Mean followed by the same letter(s) within each column do not differ statistically (p= 0.05).
111 to 332 (Treat/Treatment): $N_1P_1K_1$ to$N_3P_3K_{2;}$ NTP: number of tubers per plant, FTW: fresh tuber weight [g], STY: small tuber yield [$t.ha^{-1}$], MTY: medium tuber yield [$t.ha^{-1}$], LTY: large tuber yield [$t.ha^{-1}$], MATY: marketable tuber yield [$t.ha^{-1}$], UMATY: unmarketable tuber yield [$t.ha^{-1}$], TTY: total tuber yield [$t.ha^{-1}$].

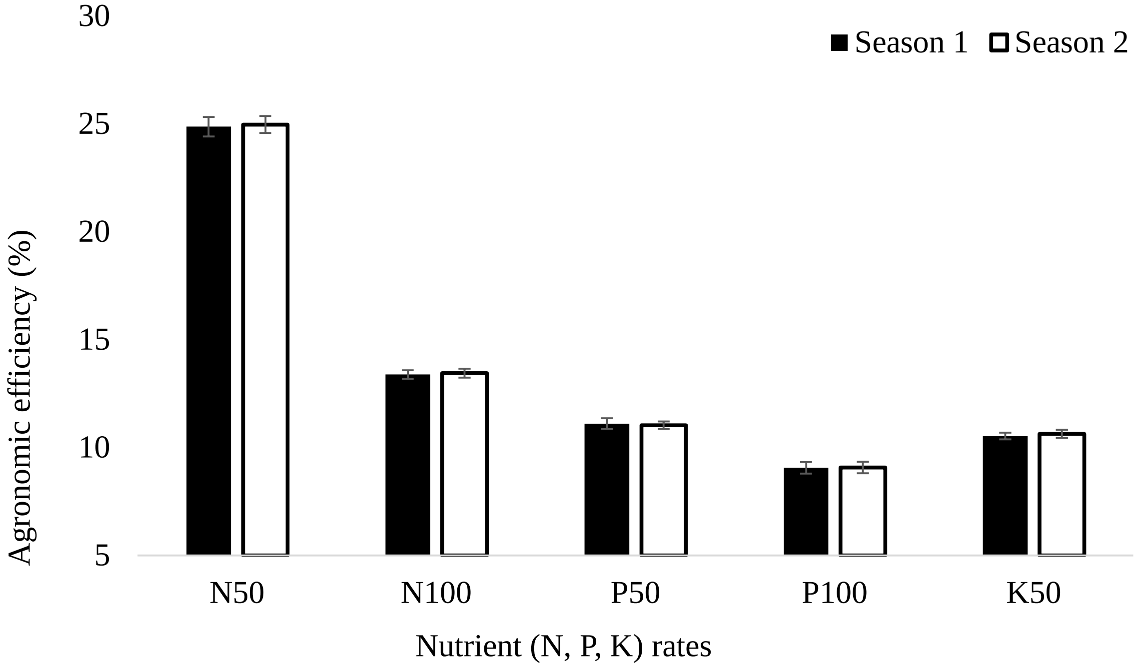
Agronomic efficiency (AE) of N, P and K for potato as influenced by location, season and nutrient rates

With respect to Agronomic Efficiency (AE) of nitrogen and phosphorus, results of pooled data (across seasons and locations) t-test revealed that AE was significant ($p < 0.05$) for both nutrients. According to the results, nutrient AE decreased with increasing nutrient rate, N_{50} (24.93%) and P_{50} (11.06%) recorded higher agronomic efficiency. Application of N_{100} rate decrease agronomic efficiency by 46.13% compared with N_{50} rate application. Compared with P_{50} rate application, application of P_{100} rate led to a decrease of 18.08% in agronomic efficiency. The results also showed that effects of location were significant ($p < 0.05$) for N_{50} nutrient only and non-significant ($p > 0.05$) for other nutrient rates (N_{100}, P_{50}, P_{100} and K_{50}) even though in general Mudende location responded better to nutrient rates application than Rwerere location. With N_{50} rate application, Mudende location increased agronomic efficiency by 15.56% compared with Rwerere location. Effects of season on nutrient agronomic efficiency was always not significant ($p > 0.05$) even though season 2 recordedslightly higher values compared with season 1.



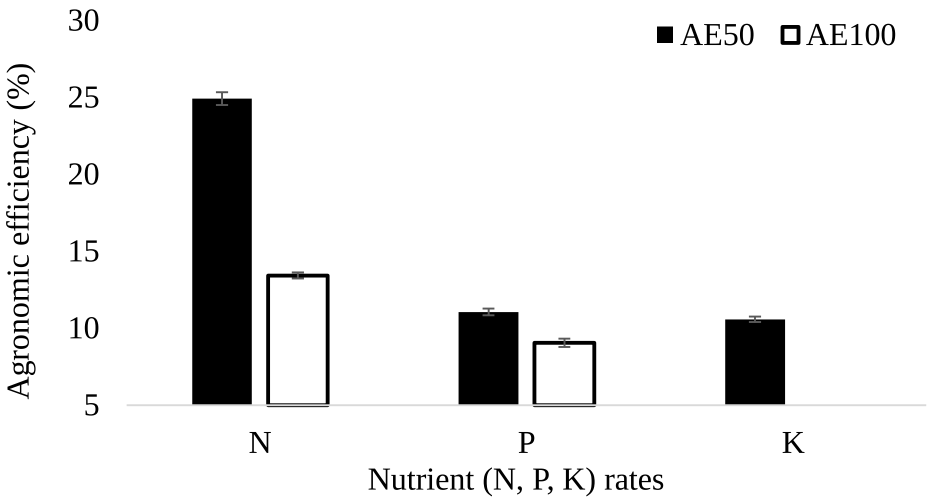
Error bar: ± standard error, significance level: p= 0.05

Figure 4.7 Effects of location on agronomic efficiency



Error bar: ± standard error, significance level: p= 0.05

Figure 4.8 Effects of season on agronomic efficiency



Error bar: ± standard error, significance level: p= 0.05

Figure 4.9 Effects of N, P and K rates on agronomic efficiency

However, higher AE was recorded with N_{50} [(26.73 ± 0.44)% [Mudende] and (24.97 ± 0.39)% [Season 2])] while lower AE was observed with P_{100} [(8.92 ± 0.26)% [Rwerere] and (9.07 ± 0.27)% [Season 1]]. With regard to results observed across seasons and locations, N_2 displayed higher AE [(24.93 ± 0.42)%] whereas P_3 depicted lower AE [(9.06 ± 0.27)%].

4.3.4 Relationship and principal component analysis for potato growth and yield attributes

Correlation between aggregate potato tuber yield and potato growth and yield parameters

The results on correlation between aggregate tuber yield and potato growth and yield parameters are depicted by Table 4.18. Locational and pooled analysis for the correlation coefficients between total tuber yield and potato growth and yield traits revealed that aggregate tuber yield had significant and positive correlation with stem height, leaf area index, number of tubers per plant, fresh tuber weight, medium sized tuber yield, large sized tuber yield and marketable tuber yield. In addition, the results revealed that aggregate tuber yield had a negative association with small and unmarketable tuber yield, while the correlation between total tuber yield and number of main stems per plant was not significant.

Table 4.18 Correlation between aggregate tuber yield and potato growth and yield parameters

Variable	**Total tuber yield**		
	Mudende location	**Rwerere location**	**Locations pooled**
SH 70DAE	r= 0.865***	r= 0.895***	r= 0.886***
LAI 70DAE	r= 0.842***	r= 0.870***	r= 0.856***
NS 30DAE	r= 0.018^{ns}	r= 0.016 ^{ns}	r= 0.019 ^{ns}
NTP	r= 0.998***	r= 0.999***	r= 0.997***
FTW	r= 0.996***	r= 0.999***	r= 0.997***
STY	r= -0.741***	r= -0.785***	r=- 0.764***
MTY	r= 0.997***	r= 0.998***	r= 0.997***
LTY	r=0.986***	r= 0.998***	r= 0.991***
MATY	r= 0.999***	r= 0.999***	r= 0.999***
UMATY	r= -0.740***	r= -0.783***	r= -0.763***

* Significant at P= 0.05, ** Significant at P = 0.01, *** Significant at P = 0.001
DAE: days after emergence, SH: stem height, SN: stem number per plant, NTP: number of tubers per plant, FTW: fresh tuber weight [g], STY: small tuber yield [$t.ha^{-1}$], MTY: medium tuber yield [$t.ha^{-1}$], LTY: large tuber yield [$t.ha^{-1}$], MATY: marketable tuber yield [$t.ha^{-1}$], UMATY: unmarketable tuber yield [$t.ha^{-1}$].

Regression between mineral fertilizers (N, P and K) and potato yield components

Multiple regression analysis was used to determine the extent to which there was a relationship between a dependent (predicted) variable (tuber yield attribute) and three independent (predictor or explanatory) variables (N, P and K nutrient fertilizer). Three independent variables (N, P and K nutrient fertilizer) were used to predict the value of a dependent variable (tuber yield attribute) (Table 4.19).

Multiple regression between mineral fertilizers (N, P and K) and potato growth, yield and yield components

The results of multiple regression analysis on single and pooled analysis bases revealed that the relationships between Nitrogen, Phosphorus and Potassium fertilizer application rates and all dependent variables were significant (Table 4.19). The relationships were positive for number of tubers per plant, fresh tuber weight, medium sized tuber yield, large sized tuber yield, marketable tuber yield and total tuber yield whereas they were negative for small and unmarketable tuber yield. The relationships were the most conspicuous for marketable (R^2= 0.82 [Rwerere]) and medium tuber yield (R^2= 0.82 [Rwerere]) followed by total tuber yield (R^2= 0. 81 [Mudende]) as evidenced by their higher values of coefficient of determination. The results associated with multiple regression between mineral fertilizers (N, P and K) and yield components are depicted by Table 4.19.

Table 4.19 Multiple regression between mineral fertilizers (N, P and K) and potato yield attributes

Dep. variable	R^2	Intercept	N	P	K	Regression Equation	Loc.
NTP	0.75***	-3.35	2.11	1.43	1.67	NTP= 2.11N + 1.43P + 1.67K - 3.35	L_1
	0.81***	-4.70	2.22	1.47	1.71	NTP= 2.22N + 1.47P + 1.71K - 4.70	L_2
	0.75***	-4.02	2.17	1.45	1.69	NTP= 2.17N + 1.45P + 1.69K - 4.02	$L_{1\&2}$
FTW	0.76***	-27.71	17.17	11.65	13.63	FTW= 17.17N + 11.65P + 13.63K – 27.71	L_1
	0.80***	-35.51	17.18	11.25	13.10	FTW= 17.18N + 11.25P + 13.10K – 35.51	L_2
	0.74***	-31.61	17.17	11.45	13.37	FTW= 17.17N + 11.45P + 13.37K – 31.61	$L_{1\&2}$
STY	0.53***	3.74	-0.36	-0.22	-0.27	STY= 3.74 -0.36N – 0.22P – 0.27K	L_1
	0.61***	3.89	-0.38	-0.21	-0.27	STY= 3.89 - 0.38N – 0.21P – 0.27K	L_2
	0.56***	3.82	-0.37	-0.21	-0.27	STY= 3.82 - 0.37N – 0.21P – 0.27K	$L_{1\&2}$
MTY	0.75***	-9.48	4.58	3.15	3.66	MTY= 4.58N + 3.15P + 3.66K – 9.48	L_1
	0.82***	-11.67	4.52	2.97	3.49	MTY= 4.52N + 2.97P + 3.49K – 11.67	L_2
	0.73***	-10.58	4.55	3.06	3.58	MTY= 4.55N + 3.06P + 3.58K – 10.58	$L_{1\&2}$
LTY	0.74***	-5.07	2.47	1.68	1.96	LTY= 2.47N + 1.68P + 1.96K – 5.07	L_1
	0.81***	-6.68	2.59	1.70	2.00	LTY= 2.59N + 1.70P + 2.00K – 6.68	L_2
	0.74***	-5.87	2.53	1.69	1.98	LTY= 2.53N + 1.69P + 1.98K – 5.87	$L_{1\&2}$
UMATY	0.53***	3.73	-0.35	-0.21	-0.27	UMARTY= 3.73 – 0.35N – 0.21P – 0.27K	L_1
	0.60***	3.89	-0.38	-0.21	-0.26	UMARTY= 3.89 – 0.38N – 0.21P – 0.26K	L_2
	0.56***	3.81	-0.37	-0.21	-0.27	UMARTY= 3.81 – 0.37N – 0.21P – 0.27K	$L_{1\&2}$
MATY	0.76***	-14.55	7.05	4.82	5.62	MARTY= 7.05N + 4.82P + 5.62 K– 14.55	L_1
	0.82***	-18.34	7.11	4.67	5.49	MARTY= 7.11N + 4.67P + 5.49K – 18.34	L_2
	0.74***	-16.44	7.08	4.75	5.56	MARTY= 7.08N + 4.75P + 5.56K – 16.44	$L_{1\&2}$
TTY	0.74***	-10.82	6.69	4.61	5.35	TTY= 6.69N + 4.61P + 5.35K – 10.82	L_1
	0.81***	-14.46	6.73	4.46	5.23	TTY= 6.73N + 4.46P + 5.23K – 14.46	L_2
	0.73***	-12.64	6.71	4.53	5.29	TTY= 6.71N + 4.53P + 5.29K – 12.64	$L_{1\&2}$

* Significant at P= 0.05, ** Significant at P = 0.01, *** Significant at P = 0.001

NTP: number of tubers per plant, FTW: fresh tuber weight [g], STY: small tuber yield [$t.ha^{-1}$], MTY: medium tuber yield [$t.ha^{-1}$], LTY: large tuber yield [$t.ha^{-1}$], MATY: marketable tuber yield [$t.ha^{-1}$], UMATY: unmarketable tuber yield [$t.ha^{-1}$], TTY: total tuber yield [$t.ha^{-1}$], L_1: location 1 (Mudende), L_2 :location 2 (Rwerere), $L_{1\&2}$: L_1 and L_2 data pooled (Mudende and Rwerere pooled).

Quadratic regression: mathematical modeling for estimating the agronomically optimum nutrient (N, P) rate

The agronomic optimum nitrogen (N) rate (N_{AOp} [$kgNha^{-1}$]) was determined by calculating the first derivative of the N-derived potato tuber yield response curve to the N application rate, which was described as a quadratic function. The results on modeling for agronomic optimum nutrient (N, P) rates and responses of potato tuber yield on the nutrient application are displayed by Table 4.20and Figures 4.10-4.13, respectively.

Table 4.20 Modeling for agronomic optimum nutrient (N, P) rates

In.Var.	**Interc.**	**Re.Coe. β_1**	**Re.Coe. β_2**	**Quadratic Equation**	**Nutr. AOp.**	**R^2**	**Loc.**
	10894	400.79	-2.67	$Y=400.79x-2.67x^2+10894$	74.97kg ha^{-1}	0.58***	Mudende
N	7124.2	327.97	-1.93	$Y=327.97x–1.93x^2+7124.2$	84.97 kg ha^{-1}	0.56***	Rwerere
	14860	133.50	-0.41	$Y=133.50x–0.41x^2+ 14860$	NA	0.20ns	Mudende
P	10981	128.08	-0.39	$Y=128.08x–0.39x^2 + 10981$	NA	0.22ns	Rwerere

*** Significant at P = 0.001, ns: not significant.
N: nitrogen, P: phosphorus, In.Var.: independent variable, Interc.: intercept, Re. Coe.: regression coefficient, Nutr.AoP.: nutrient agronomic optimum, R^2: coefficient of determination, Loc: location,NA: not applied.

To represent the response of potato tuber yield on the applied dose of N, a quadratic regression model was used. The intercept and both regression coefficients of the quadratic model were significant ($p < 0.05$); meaning that with the model, the independent variable (N rate) predicts reliably the dependent variable (potato yield). The coefficient of determination (R^2) was 58% [Mudende] and 56% [Rwerere], meaning that 58% [Mudende] and 56% [Rwerere] of variance in potato tuber yield can be predicted from N nutrient rate application. The positive coefficients for x suggested that the fertilizer application had positive effects on potato tuber yield. The main effects of N at both locations on potato tuber yield were evaluated by comparing their corresponding coefficients in quadratic equations. The largest value was observed for the coefficient of x (400.79) at Mudende location, indicating that N showed the highest influence on potato tuber yield in this location.

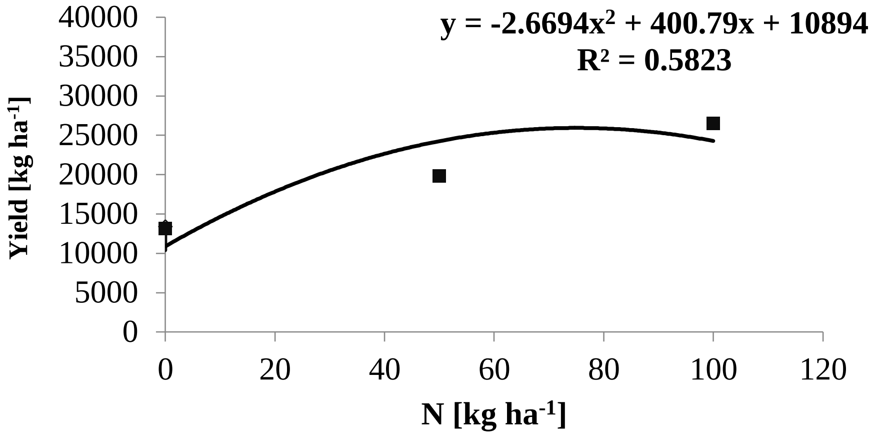


Figure 4.10 Response of potato tuber yield on N application at Mudende

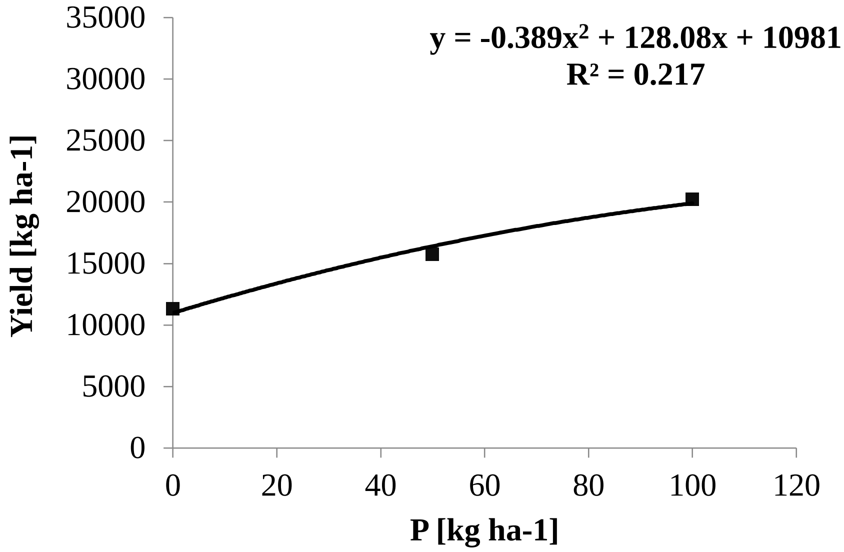


Figure 4.11 Response of potato tuber yield on P application at Mudende

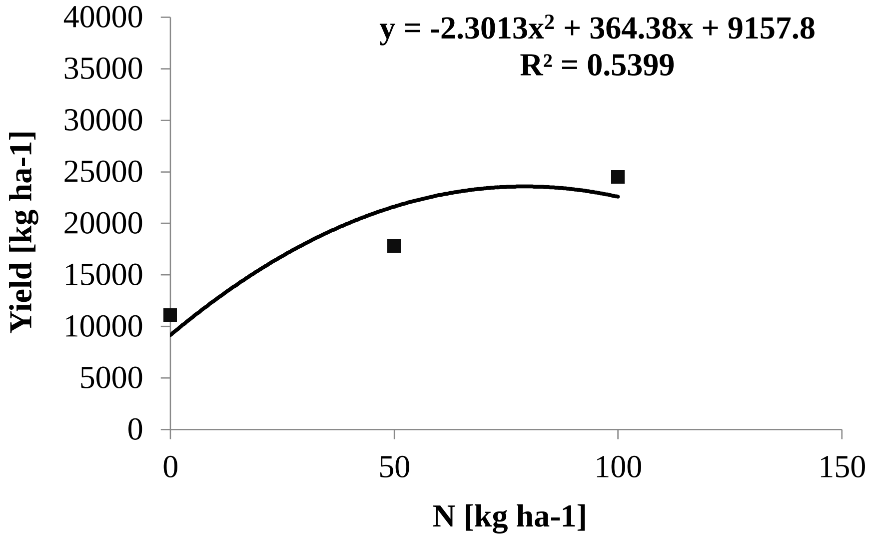


Figure 4.12 Response of potato tuber yield on N application at Rwerere

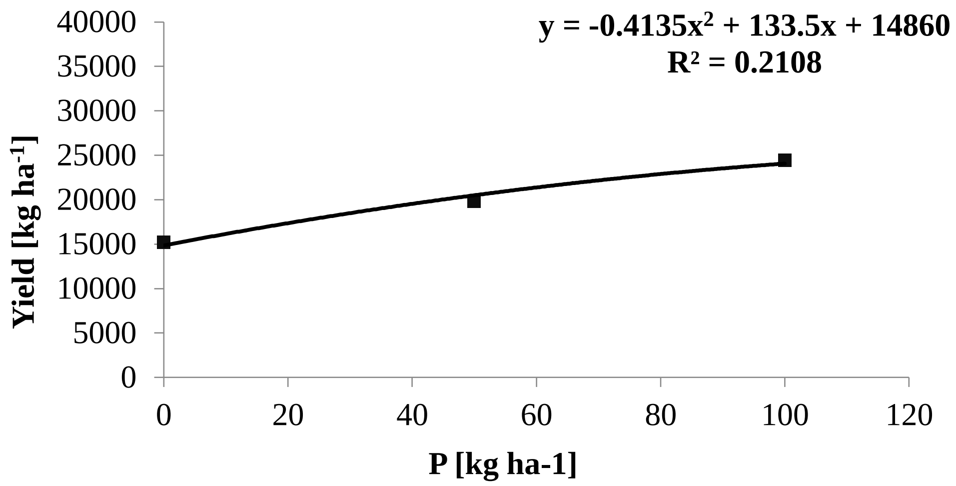


Figure 4.13 Response of potato tuber yield on P application at Rwerere

With regard to the response of potato tuber yield on the applied dose of P nutrient, also a quadratic regression model was used to construct the yield function. The graph constructed from the research data displayed a shape with a sharp slope, without concavity as it was made of almost a straight line. The intercept and both coefficients of the response model were not significant ($p > 0.05$) at both locations, meaning that with the model, the independent variable (P rate) does not predict reliably the dependent variable (potato yield). The quadratic model was not appropriate to display potato yield response to P nutrient rate application. As consequence, agronomic optimum rate of P nutrient was not found.

Principal components analysis for potato growth and potato yield attributes

The results of principal component analysis revealed that, out of ten, only the first two components had Eigen values up to 1.0 as depicted by scree plot figures (Figures 4.14, 4.15 and 4.18), presenting cumulative variance of 87.5% [Mudende], 89.5% [Rwerere] and 88.6% [Mudende and Rwerere pooled]. The results on PCA and loading matrix are depicted by Tables 4.21-4.22 and Figures 4.16, 4.17 and 4.19; respectively. Principal component one (PC1), with Eigen value of 7.73 [Mudende], 7.79 [Rwerere] and 7.85 [pooled basis] contributed 77.3% [Mudende], 77.9% [Rwerere] and78.5% [Pooled basis] of the total variability, while PC2, with Eigen value of 1.02 [Mudende], 1.00 [Rwerere] and 1.00 [pooled basis] accounted for 10.2% [Mudende], 10.0% [Rwerere]and 11.1% [Pooled basis] of total variability observed among the 18 treatments. The pattern of observed variables within unobserved ones or principle components was similar for locational and pooled analyses. The first PC was more related to stem height (70 days after emergence), leaf area index (70 days after emergence), number of tubers per plant, fresh tuber weight, small sized tuber yield, medium sized tuber yield, large sized tuber yield, unmarketable tuber yield and marketable tuber yield whereas the second PC was more associated with number of main stems per plant.The first PC depicted strong positive loadings with respect to number of tubers per plant, fresh tuber weight and marketable tuber yield (0.99 [Mudende], 0.99 [Rwerere] and 0.99 [Pooled basis]), medium sized tuber yield (0.98 [Mudende], 0.99[Rwerere] and [Pooled basis]), large sized tuber yield (0.98 [Mudende], [Rwerere] and [Pooled basis]), stem height (0.89 [Mudende], 0.90 [Rwerere] and [Pooled basis]) and leaf area index (0.85 [Mudende], 0.86 [Rwerere] and [Pooled basis]). The PC also showed negative strong loadings with regard to small sized tuber yield (0.82 [Mudende], 0.84 [Rwerere] and [Pooled basis]) and unmarketable tuber yield (0.82 [Mudende], 0.84 [Rwerere] and [Pooled basis]). The second PC was characterized by strong positive loadings for number of main stems per plant (0.92 [Mudende], 0.99 [Rwerere] and [Pooled basis]). The second PC accounted for 10.2% [Mudende], 10.0% [Rwerere] and 11.1% [Pooled basis] of total variability and contained one variable, number of main stems per plant. According to the results, the contribution of the agronomic trait to the variation of potato yield was the least compared to inputs of the others, but positive.

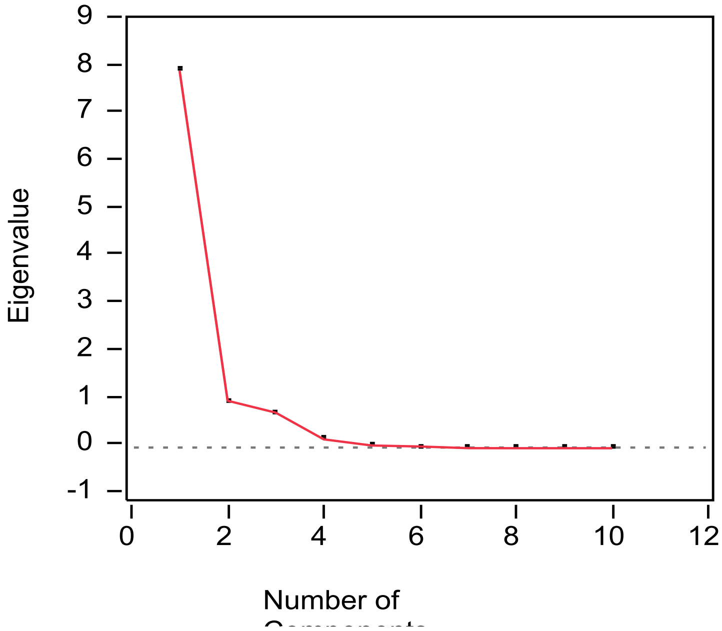


Figure 4.14 Scree plot for potato growth and yield attributes at Mudende

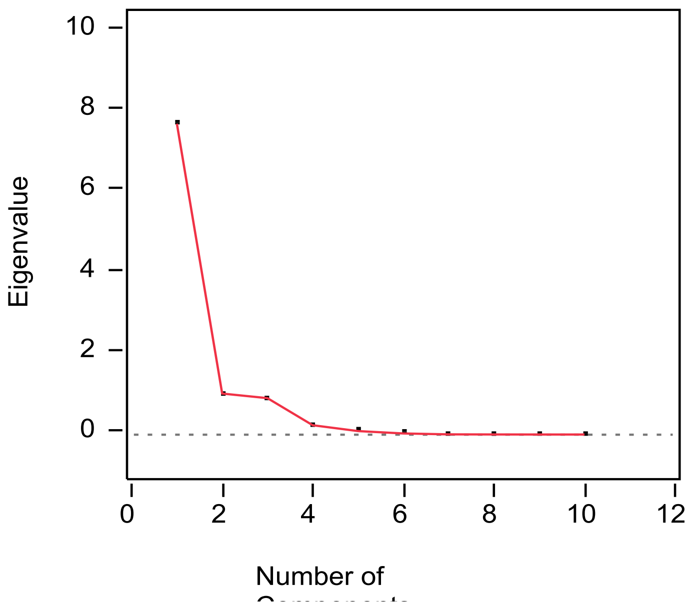


Figure 4.15 Scree plot for potato growth and yield attributes at Rwerere

Table 4.21 Loading Matrix for potato growth and yield attributes [Locational basis]

	Mudende (L_1)		Rwerere (L_2)	
	Princ.1	**Princ.2**	**Princ.1**	**Princ.2**
SH70DAE	**0.89**	0.15	**0.90**	0.07
SN30DAE	0.02	**0.92**	0.02	**0.99**
LAI70DAE	**0.85**	0.19	**0.86**	0.07
NTP	**0.99**	0.02	**0.99**	0.01
TW	**0.99**	0.01	**0.99**	0.01
STY	**-0.82**	0.23	**-0.84**	0.11
MTY	**0.98**	0.02	**0.99**	0.01
LTY	**0.98**	-0.00	**0.98**	0.00
MATY	**0.99**	0.01	**0.99**	0.00
UNMATY	**-0.82**	0.23	**-0.84**	0.11

ST: stem height, SN: number of main stems per plant, DAE: days after emergence, NTP: number of tubers per plant, FTW: fresh tuber weight, STY: small tuber yield, MTY: medium tuber yield, LTY: large tuber yield, MATY: marketable tuber yield, UMATY: unmarketable tuber yield, Princ.: Principal component.

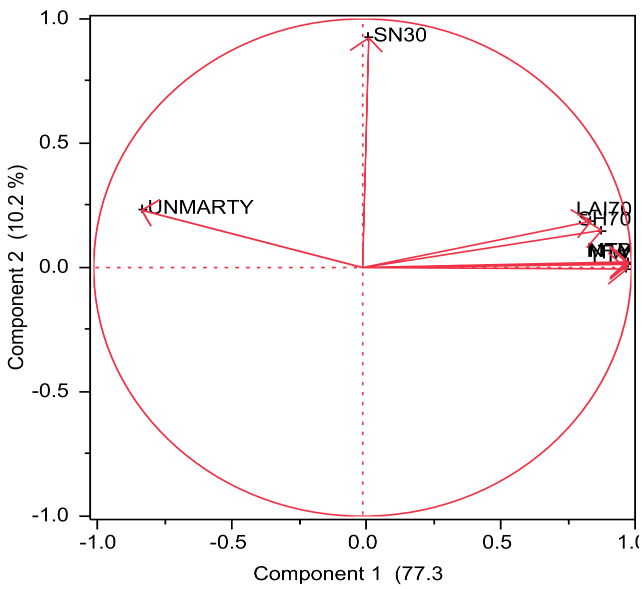


Figure 4.16 Principal components for potato growth and yield attributes [Mudende]

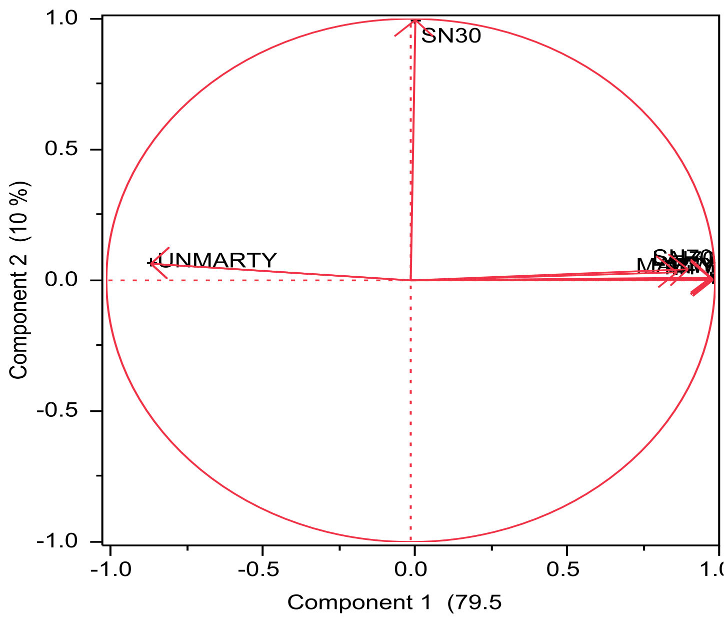


Figure 4.17 Principal components for potato growth and yield attributes [Rwerere]

Table 4.22 Loading Matrix potato growth and yield attributes [Pooled basis]

	Princ.1	**Princ.2**
SH70DAE	**0.90**	0.07
SN30DAE	0.02	**0.99**
LAI70DAE	**0.86**	0.07
NTP	**0.99**	0.01
TW	**0.99**	0.01
STY	**-0.84**	0.11
MTY	**0.99**	0.01
LTY	**0.98**	0.00
MATY	**0.99**	0.00
UNMATY	**-0.84**	0.11

ST: stem height, DAE: days after emergence, SN: stem number per plant, NTP: number of tubers per plant, FTW: fresh tuber weight, STY: small tuber yield, MTY: medium tuber yield, LTY: large tuber yield, MATY: marketable tuber yield, UMATY: unmarketable tuber yield, Princ.: principal.

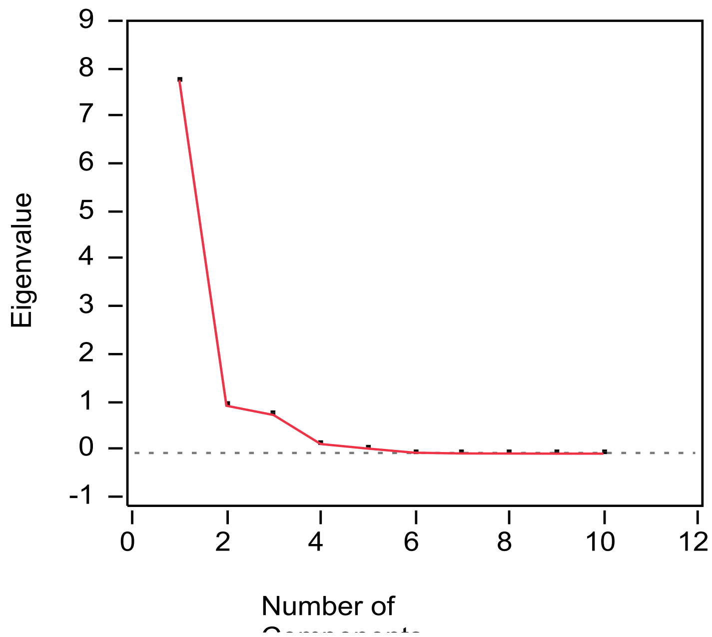


Figure 4.18 Scree plot for potato attributes [Pooled basis]

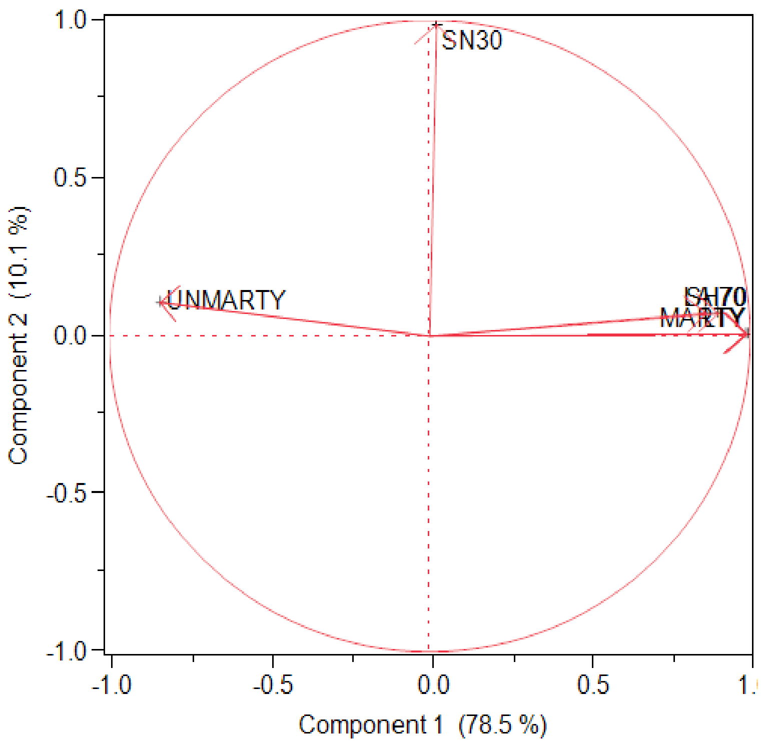


Figure 4.19 Pooled Principal components for potato growth and yield attributes

4.4 Effect of season, Nitrogen, Phosphorus and Potassium on potato quality attributes

4.4.1 Main effect of season, Nitrogen, Phosphorus and Potassium on potato quality attributes in each location

The results of analysis of variance on the main effect of season, N, P and K on potato quality attributes at Mudende and Rwerere are presented in Tables 4.23 and 4.24, respectively. The analysis of variance revealed that the main effect of season was not significant ($p > 0.05$) on all potato quality attributes, at both locations. The analysis of variance revealed that the main effects of N, P and K fertilizer rates were significant ($p < 0.05$) on specific gravity, starch, dry matter (Appendices 5 and 8), reducing sugars, crude protein, ascorbic acid and crude ash content, at both locations.

Application of N_{100} increased reducing sugar up to 3.22% (Mudende) and 3.51% (Rwerere); crude protein up 3.16% (Mudende) and 2.55% (Rwerere); ascorbic acid up to 5.50% (Mudende) and 5.45% (Rwerere) compared with the unfertilized control N_0. The treatment also led to a decrease of 0.18% in specific gravity at both locations; 2.66% (Mudende) and 2.87% (Rwerere) in starch; 2.70% (Mudende) and 2.87% (Rwerere) in dry matter; and 5.08% (Mudende) and 5.04% (Rwerere) in crude ash content versus to the non-fertilized control N_0. P_{100} application led to an increase of 7.84% (Mudende) and 7.74% (Rwerere) in crude protein; and 8.23% (Mudende) and 8.15% (Rwerere) in vitamin C. The treatment also resulted in a decrease of 0.64% in specific gravity at both locations; 8.44% (Mudende) and 8.64% (Rwerere) in starch; 8.61% (Mudende) and 8.67% (Rwerere) in dry matter; 8.19% (Mudende) and 8.20% (Rwerere) in reducing sugars; and 10.0% (Mudende) and 9.92% (Rwerere) in crude ash content versus to the non-fertilized control P_0. Application of K_{50} increased specific gravity up to 0.46% at both locations; starch up to 6.30% (Mudende) and 6.50% (Rwerere); dry matter up to 6.26% (Mudende) and 6.56% (Rwerere); crude protein up to 6.41% (Mudende) and 7.00% (Rwerere); ascorbic acid up to 6.85% (Mudende) and 6.79% (Rwerere) compared with the unfertilized control K_0. The treatment also led to a decrease of 6.99% (Mudende) and 6.67% (Rwerere) in reducing sugar content; and 5.93% (Mudende) and 6.67% (Rwerere) in crude ash content versus to the non-fertilized control K_0.

Table 4.23 Effect of season, nitrogen, phosphorus and potassium on potato quality attributes at Mudende

		SG	ST (%)	DM (%)	RS (%)	PRT (%)	VTC (mg/100g	Ash) (%)
N	0	1.090 ± 0.00^{a}	15.79 ± 0.23^{a}	21.08 ± 0.31^{a}	0.217 ± 0.00^{b}	1.58± 0.03^{b}	20.90 ± 0.33^{b}	1.18 ± 0.02^{a}
	50	1.088 ± 0.00^{b}	15.47 ± 0.26^{b}	20.67± 0.34^{b}	0.221 ± 0.00^{ab}	1.62 ± 0.03^{a}	21.77 ± 0.36^{a}	1.15 ± 0.02^{b}
	100	1.088 ± 0.00^{b}	15.37 ± 0.24^{b}	20.51 ± 0.33^{b}	0.224 ± 0.00^{a}	1.63 ± 0.02^{a}	22.05 ± 0.36^{a}	1.12 ± 0.02^{c}
LSD		0.001	0.22	0.30	0.004	0.02	0.31	0.02
P	0	1.091 ± 0.00^{a}	16.00 ± 0.22^{a}	21.38 ± 0.29^{a}	0.232 ± 0.00^{a}	1.53 ± 0.03^{b}	20.54 ± 0.36^{b}	1.20 ± 0.02^{a}
	50	1.091 ± 0.00^{a}	15.99 ± 0.21^{a}	21.35 ± 0.29^{a}	0.216 ± 0.00^{b}	1.64 ± 0.02^{a}	21.95 ± 0.30^{a}	1.15 ± 0.02^{b}
	100	1.084 ± 0.00^{b}	14.65 ± 0.25^{b}	19.54 ± 0.34^{b}	0.213 ± 0.00^{b}	1.65 ± 0.02^{a}	22.23 ± 0.34^{a}	1.08 ± 0.02^{c}
LSD		0.001	0.22	0.30	0.004	0.02	0.30	0.02
K	0	1.086 ± 0.00^{b}	15.07 ± 0.21^{b}	20.12 ± 0.28^{b}	0.229 ± 0.00^{a}	1.56 ± 002^{b}	20.86 ± 0.28^{b}	1.18 ± 0.01^{a}
	50	1.091 ± 0.00^{a}	16.02 ± 0.18^{a}	21.38 ± 0.24^{a}	0.213 ± 0.00^{b}	1.66 ± 0.02^{a}	22.29 ± 0.26^{a}	1.11 ± 0.02^{b}
LSD		0.0009	0.18	0.25	0.003	0.02	0.25	0.01
Season	1	1.089 ± 0.00	15.56 ± 0.20	20.77 ± 0.27	0.220 ± 0.00	1.61 ± 0.02	21.58 ± 0.29	1.15 ± 0.02
	2	1.089 ± 0.00	15.53 ± 0.20	20.74 ± 0.27	0.221 ± 0.00	1.61 ± 0.02	21.57 ± 0.28	1.14 ± 0.02
LSD		0.0009	0.18	0.24	0.003	0.02	0.25	0.01
Mean		1.089	15.54	20.75	0.221	1.61	21.57	1.15
CV		0.25	3.51	3.59	4.21	3.58	3.57	3.58

Means followed by the same letter(s) within each column do not differ statistically (p= 0.05).

SG: Specific Gravity; ST: Starch; DM: Dry Matter; RS: Reducing Sugar; PRT: Protein, VTC: Vitamin C.

Table 4.24 Effect of season, Nitrogen, Phosphorus and Potassium on potato quality attributes at Rwerere

		SG	ST (%)	DM (%)	RS (%)	PRT (%)	VTC (mg/100g)	Ash (%)
Season	1	1.090 ± 0.00	15.75 ± 0.20	21.28 ± 0.27	0.23 ± 0.00	1.62± 0.02	21.78 ± 0.29	1.16 ± 0.02
	2	1.090 ± 0.00	15.72 ± 0.20	21.25 ± 0.27	0.23 ± 0.00	1.63 ± 0.02	21.77 ± 0.28	1.16 ± 0.02
LSD		0.0009	0.18	0.25	0.003	0.02	0.25	0.01
N	0	1.091 ± 0.00^{a}	15.99 ± 0.23^{a}	21.61 ± 0.31^{a}	0.228 ± 0.00^{b}	1.60± 0.03^{b}	21.10 ± 0.33^{b}	1.19 ± 0.02^{c}
	50	1.089 ± 0.00^{b}	15.68 ± 0.26^{b}	21.19 ± 0.34^{b}	0.233 ± 0.00^{a}	1.63± 0.03^{a}	21.97 ± 0.36^{a}	1.16 ± 0.02^{b}
	100	1.089 ± 0.00^{b}	15.53 ± 0.24^{b}	20.99 ± 0.33^{b}	0.236 ± 0.00^{a}	1.64 ± 0.02^{a}	22.25 ± 0.33a	1.13 ± 0.02^{a}
LSD		0.001	0.22	0.30	0.004	0.02	0.31	0.02
P	0	1.092 ± 0.00^{a}	16.21 ± 0.22^{a}	21.91 ± 0.30^{a}	0.244 ± 0.00^{a}	1.55 ± 0.03^{b}	20.74 ± 0.36^{b}	1.21 ± 0.02^{c}
	50	1.092 ± 0.00^{a}	16.19 ± 0.21^{a}	21.88 ± 0.29^{a}	0.229 ± 0.00^{b}	1.66 ± 0.02^{a}	22.15 ± 0.30^{a}	1.17 ± 0.02^{b}
	100	1.085 ± 0.00^{b}	14.81 ± 0.26^{b}	20.01 ± 0.35^{b}	0.224 ± 0.00^{c}	1.67 ± 0.02^{a}	22.43 ± 0.34^{a}	1.09 ±0.02^{a}
LSD		0.001	0.22	0.30	0.003	0.02	0.31	0.02
K	0	1.087 ± 0.00^{b}	15.24 ± 0.21^{b}	20.59 ± 0.28^{b}	0.240 ± 0.00^{a}	1.57 ± 002^{b}	21.06 ± 0.28^{b}	1.20 ± 0.01^{b}
	50	1.092 ± 0.00^{a}	16.23 ± 0.18^{a}	21.94 ± 0.24^{a}	0.224 ± 0.00^{b}	1.68 ± 0.02^{a}	22.49 ± 0.26^{a}	1.12 ± 0.02^{a}
LSD		0.0009	0.18	0.24	0.003	0.02	0.25	0.01
Season	1	1.090 ± 0.00	15.75 ± 0.20	21.28 ± 0.27	0.23 ± 0.00	1.62± 0.02	21.78 ± 0.29	1.16 ± 0.02
	2	1.090 ± 0.00	15.72 ± 0.20	21.25 ± 0.27	0.23 ± 0.00	1.63 ± 0.02	21.77 ± 0.28	1.16 ± 0.02
LSD		0.0009	0.18	0.25	0.003	0.02	0.25	0.01
Mean		1.090	15.74	21.26	0.232	1.62	21.77	1.16
CV		0.25	3.47	3.47	4.13	3.41	3.54	3.57

Mean followed by the same letter(s) within each column do not differ statistically (p= 0.05).

SG: Specific Gravity; ST: Starch; DM: Dry Matter; RS: Reducing Sugar; PRT: Protein, VTC: Vitamin C.

4.4.2 Interaction effect of season, Nitrogen, Phosphorus and Potassium on potato quality attributes in each location

The effect of season × N× P× K interaction on all potato quality attributes was not significant ($p > 0.05$) at both locations. The fertilizer rates affected potato quality attributes in similar ways at both seasons across locations. The results of analysis of variance on the N× P × K interaction effects on potato quality attributes are presented in Tables 4.25 (Mudende) and 4.26 (Rwerere).

The analysis revealed that the N× P × K interaction effects were significant ($p < 0.05$) on specific gravity, starch, dry matter, reducing sugar, crude protein, ascorbic acid and crude ash content in both locations. Application of$N_{100}P_{100}K_{50}$ treatment combination increased crude protein by 23.78% (Mudende) and 22.22% (Rwerere), ascorbic acid by 26.64% (Mudende) and 26.48% (Rwerere). The treatment combination decreased crude ash content by 22.4% (Mudende) and 22.90% (Rwerere) versus to the control $N_0P_0K_0$. $N_0P_0K_{50}$ treatment combination recorded the highest specific gravity, starch and dry matter content. It increased specific gravity up to 0.64% at both locations, starch up to 8.61% (Mudemde) and 8.81% (Rwerere) and dry matter up to 8.5% (Mudende) and 8.82% (Rwerere) versus to the non-fertilized control $N_0P_0K_0$.Compared with $N_{100}P_{100}K_{50}$ treatment combination which recorded the highest tuber yield, $N_0P_0K_{50}$ treatment combinationled to an increase of 0.73% (Mudende) and 0.82% (Rwerere) in specific gravity, 10.52% (Mudemde) and 10.71% (Rwerere) in starch, and 11.03% (Mudende) and 10.74% (Rwerere) in dry matter. $N_{100}P_0K_0$ recoded the highest reducing sugar content. It increased reducing sugar content by 8.66% (Mudende) and 8.71% (Rwerere) compared with the non-fertilized control $N_0P_0K_0$, the treatment combination also caused an increase of 18.96% (Mudende) and 19.09% (Rwerere) in reducing sugar content versus to $N_{100}P_{100}K_{50}$ treatment combination which recorded the highest potato tuber yield.

Table 4.25 Interaction effect of Nitrogen, Phosphorus and Potassium on potato quality attributes at Mudende

Treat	SG	ST (%)	DM (%)	RS (%)	PRT (%)	VTC (mg/100g)	Ash (%)
$N_0P_{100}K_{50}$	1.088 ± 0.00^{f}	15.30 ± 0.52^{f}	20.40 ± 0.70^{e}	0.198 ± 0.01^{g}	1.63 ± 0.06^{bcde}	21.60 ± 0.75^{cde}	1.09 ± 0.04^{g}
$N_0P_{50}K_{50}$	1.094 ± 0.00^{ab}	16.99 ± 0.52^{ab}	21.99 ±0.70^{ab}	0.211 ±0 .01^{ef}	1.66 ± 0.06^{bcd}	23.00 ± 0.74^{bc}	1.15 ± 0.04^{bcde}
$N_{50}P_{100}K_{50}$	1.088 ± 0.00^{f}	15.30 ± 0.52^{f}	20.39 ± 0.70^{e}	0.204 ± 0.01^{fg}	1.75 ± 0.04^{a}	23.62 ± 0.63^{a}	1.01± 0.06^{h}
$N_{100}P_{50}K_{50}$	1.093 ± 0.00^{bc}	16.29 ± 0.52^{bc}	21.72 ± 0.70^{bc}	0.211 ± 0.01^{ef}	1.67 ± 0.06^{bc}	22.55 ± 0.74b	1.11 ± 0.04^{fg}
$N_{50}P_{50}K_{50}$	1.092 ± 0.00^{bcd}	16.24 ± 0.53^{bcd}	21.66 ± 0.71^{bc}	0.210 ± 0.01^{ef}	1.68 ± 0.06b	22.57 ± 0.77^{b}	1.14 ± 0.04^{cdef}
$N_{100}P_{100}K_{50}$	1.088 ± 0.00^{f}	15.30 ± 0.52^{f}	20.40 ± 0.70^{e}	0.211 ± 0.01^{ef}	1.77 ± 0.07^{a}	23.91 ± 0.87^{a}	1.00 ± 0.05^{h}
$N_0P_{50}K_0$	1.090 ± 0.00^{def}	15.74 ± 0.53^{def}	20.99 ± 0.71^{cde}	0.217 ± 0.01^{de}	1.58 ± 0.05^{efg}	20.95 ± 0.72^{efg}	1.19 ± 0.04^{b}
$N_{50}P_{50}K_0$	1.089 ± 0.00^{ef}	15.64 ± 0.56^{ef}	20.86 ± 0.75^{de}	0.224 ± 0.01^{bcd}	1.63 ± 0.05^{bcde}	22.87 ± 0.77^{bcd}	1.18 ± 0.04^{bc}
$N_{50}P_{100}P_0$	1.079 ± 0.00^{h}	13.65 ± 0.76^{h}	18.24 ± 1.03^{g}	0.222 ± 0.01^{cd}	1.60 ± 0.06^{ef}	21.45 ± 0.78^{cdef}	1.13 ± 0.04^{def}
$N_0P_{100}K_0$	1.085 ± 0.00^{g}	14.70 ± 0.52^{g}	19.59 ± 0.70^{f}	0.227 ± 0.01^{bc}	1.57 ± 0.06^{fg}	20.84 ± 0.81^{fg}	1.14 ± 0.04^{def}
$N_{100}P_{100}K_0$	1.079 ± 0.00^{h}	13.65 ± 0.65^{h}	18.21 ± 0.87^{g}	0.223 ± 0.01^{bcd}	1.62 ± 0.06^{cde}	21.95 ± 0.74^{bc}	1.12 ± 0.04^{efg}
$N_{100}P_{50}K_0$	1.089 ± 0.00^{ef}	15.52 ± 0.51^{ef}	20.86 ± 0.75^{de}	0.226 ± 0.01^{bc}	1.61 ± 0.06^{def}	21.78 ± 0.75^{cd}	1.16 ± 0.04^{bcd}
$N_{50}P_0K_{50}$	1.093 ± 0.00^{abc}	16.44 ± 0.42^{abc}	22.02 ± 0.56^{ab}	0.225 ±0.01^{bcd}	1.62 ± 0.05^{cdef}	21.70 ± 0.76^{cde}	1.15 ± 0.04^{bcde}
$N_0P_0K_{50}$	1.096 ± 0.00^{a}	16.91 ± 0.59^{a}	22.65 ± 0.79^{a}	0.223 ± 0.01^{bcd}	1.60 ± 0.06^{ef}	21.16 ± 0.74^{defg}	1.19 ± 0.04^{b}
$N_{100}P_0K_{50}$	1.091 ± 0.00^{cde}	15.94 ± 0.54^{cde}	21.23 ± 0.71^{cd}	0.228 ± 0.01^{bc}	1.59 ± 0.06^{ef}	21.51 ± 0.76^{cdef}	1.13 ± 0.04^{def}
$N_0P_0K_0$	1.089 ± 0.00^{ef}	15.57 ± 0.54^{ef}	20.86 ± 0.72^{de}	0.231 ± 0.01^{b}	1.43 ± 0.07^{h}	18.88 ± 0.89^{h}	1.29 ± 0.05^{a}
$N_{50}P_0K_0$	1.089 ± 0.00^{ef}	15.57 ± 0.54^{ef}	20.82 ± 0.77^{de}	0.245 ± 0. 01^{a}	1.44 ± 0.08^{h}	19.43 ± 1.08^{h}	1.27 ± 0.03^{a}
$N_{100}P_0K_0$	1.089 ± 0.00^{ef}	15.55 ± 0.53ef	20.67 ± 0.87^{de}	0.251 ± 0.01^{a}	1.53 ± 0.06^{g}	20.60 ± 0.74^{g}	1.17 ± 0.04^{bcd}
Mean	1.089	15.54	20.75	0.221	1.61	21.57	1.15
LSD	0.003	0.54	0.74	0.009	0.06	0.76	0.04
CV	0.25	3.51	3.59	4.21	3.58	3.57	3.58

Means followed by the same letter(s) within each column do not differ statistically (p= 0.05).

SG: Specific Gravity; ST: Starch; DM: Dry Matter; RS: Reducing Sugar; PRT: Protein, VTC: Vitamin C.

Table 4.26 Interaction effect of Nitrogen, Phosphorus and Potassium on potato quality attributes at Rwerere

Treat	SG	ST (%)	DM (%)	RS (%)	PRT (%)	VTC(mg/100g)	Ash(%)
$N_0P_{100}K_{50}$	1.088 ± 0.00^{f}	15.50 ± 0.52^{f}	20.94 ± 0.71^{f}	0.207 ± 0.01^{i}	1.65 ± 0.06^{cdef}	21.80 ± 0.75^{cde}	1.10 ± 0.04^{h}
$N_0P_{50}K_{50}$	1.094 ± 0.00^{ab}	16.69 ± 0.52^{ab}	22.55 ±0.71^{ab}	0.223 ±0 .01^{efg}	1.68 ± 0.06^{cde}	22.20 ± 0.74bc	1.16 ± 0.04^{cdef}
$N_{50}P_{100}K_{50}$	1.088 ± 0.00^{f}	15.50 ± 0.52^{f}	20.94 ± 0.71^{f}	0.214 ± 0.01^{hi}	1.75 ± 0.05^{ab}	23.82 ± 0.63^{a}	1.02 ± 0.06i
$N_{100}P_{50}K_{50}$	1.093± 0.00^{bc}	16.49 ± 0.52^{bc}	22.29 ± 0.71^{bc}	0.223 ± 0.01^{efg}	1.68 ± 0.05^{cd}	22.76 ± 0.74^{b}	1.12 ± 0.04^{gh}
$N_{50}P_{50}K_{50}$	1.093 ± 0.00^{bcd}	16.44 ± 0.53^{bcd}	22.22 ± 0.72^{bcd}	0.222 ± 0.01^{fgh}	1.70 ± 0.06^{bc}	22.77 ± 0.77^{b}	1.15 ± 0.04^{cdfg}
$N_{100}P_{100}K_{50}$	1.088 ± 0.00^{f}	15.50 ± 0.52^{f}	20.94 ± 0.71^{f}	0.220 ± 0.01^{gh}	1.76± 0.05a	24.12 ± 0.88^{a}	1.01 ± 0.05^{i}
$N_0P_{50}K_0$	1.091 ± 0.00^{def}	15.94 ± 0.54^{def}	21.55 ± 0.72^{def}	0.230 ± 0.01^{def}	1.60 ± 0.05^{fg}	21.15 ± 0.73^{efg}	1.21 ± 0.04^{b}
$N_{50}P_{50}K_0$	1.090 ± 0.00^{ef}	15.84 ± 0.56^{ef}	21.41 ± 0.76e^{f}	0.237 ± 0.01^{bcd}	1.65 ± 0.05^{cdef}	22.07 ± 0.74^{bcd}	1.19 ± 0.04^{bc}
$N_{50}P_{100}P_0$	1.080 ± 0.00^{h}	13.85 ± 0.76^{h}	18.72 ± 1.03^{h}	0.232 ± 0.01^{cde}	1.62 ± 0.06fg	21.65 ± 0.78^{cdef}	1.15 ± 0.04^{cdfg}
$N_0P_{100}K_0$	1.085 ± 0.00^{g}	14.90 ± 0.52^{g}	20.13 ± 0.71^{g}	0.237 ± 0.01^{bcd}	1.59 ± 0.06gh	21.03 ± 0.81^{fg}	1.15 ± 0.04^{cdfg}
$N_{100}P_{100}K_0$	1.079 ± 0.00^{h}	13.60 ± 0.64^{h}	18.38 ± 0.87^{h}	0.233 ± 0.01^{bcd}	1.64 ± 0.05^{defg}	22.15 ± 0.74^{bc}	1.13 ± 0.04^{fgh}
$N_{100}P_{50}K_0$	1.090 ± 0.00^{ef}	15.72 ± 0.51^{ef}	21.24 ± 0.69^{ef}	0.240 ± 0.01^{bc}	1.63 ± 0.06^{efg}	21.99 ± 0.76^{cd}	1.18 ± 0.04^{bcde}
$N_{50}P_0K_{50}$	1.094 ± 0.00^{ab}	16.69 ± 0.51^{ab}	22.55 ± 0.69^{ab}	0.235 ±0.01^{bcd}	1.64 ± 0.06^{defg}	21.90 ± 0.76^{cde}	1.16 ± 0.04^{cdef}
$N_0P_0K_{50}$	1.097 ± 0.00^{a}	17.16 ± 0.58^{a}	23.19 ± 0.79^{a}	0.233 ± 0.01^{bcd}	1.62 ± 0.06^{fg}	21.36 ± 0.74^{defg}	1.21 ± 0.04^{b}
$N_{100}P_0K_{50}$	1.092 ± 0.00^{cde}	16.14 ± 0.54^{cde}	21.81 ± 0.73^{cde}	0.238 ± 0.01^{bcd}	1.60 ± 0.06^{fg}	21.71 ± 0.76^{cdef}	1.15 ± 0.04^{cdefg}
$N_0P_0K_0$	1.090 ± 0.00^{ef}	15.77 ± 0.54^{ef}	21.31 ± 0.73^{ef}	0.241 ± 0.01^{b}	1.44 ± 0.07^{i}	19.07 ± 0.90^{h}	1.31 ± 0.05a
$N_{50}P_0K_0$	1.090 ± 0.00^{ef}	15.77 ± 0.54^{ef}	21.31 ± 0.73^{ef}	0.256 ± 0.01^{a}	1.46 ± 0.08^{i}	19.62 ± 1.08^{h}	1.28 ± 0.03^{a}
$N_{100}P_0K_0$	1.090 ± 0.00^{ef}	15.74 ± 0.53^{ef}	18.38 ± 0.72^{h}	0.262 ± 0.01^{a}	1.54 ± 0.05^{h}	20.80 ± 0.74^{g}	1.19 ± 0.04^{bc}
Mean	1.090	15.74	21.26	0.232	1.62	21.77	1.16
LSD	0.003	0.54	0.73	0.009	0.05	0.77	0.04
CV	0.25	3.47	3.47	4.13	3.41	3.54	3.57

Means followed by the same letter(s) within each column do not differ statistically (p= 0.05).

SG: Specific Gravity; ST: Starch; DM: Dry Matter; RS: Reducing Sugar; PRT: Protein, VTC: Vitamin C.

4.4.3 Analysis of variance on pooled basis on potato quality attributes

Variances of homogeneity from results of the Bartlett test revealed that the mean squares of individual seasons (within location and across locations) and locations were homogenous and so a combined ANOVA on potato quality attributes was done. The results of analysis of variance on pooled basis for the main effect of location, season, N, P and K are presented in Table 4.27.

Main effect of location and season on potato quality attributes on pooled basis

The analysis revealed that the main effects of location were significant ($p < 0.05$) on all quality attributes. Rwerere location recorded the highest specific gravity, starch, dry matter, reducing sugar, crude protein, ascorbic acid and crude ash content. Compared with Mudende location, Rwerere location increased specific gravity up to 0.09%, starch up to 1.29%, dry matter up to 2.46%, reducing sugar up to 4.98, crude protein up to 0.62%, ascorbic acid up to 0.93% and crude ash content up to 0.87%. Conversely, the main effects of season on all quality attributes were not significant ($p > 0.05$).

Main effect of N, P and K on potato quality attributes pooled basis

The analysis revealed that the main effects of N, P and K on all quality attributes were significant ($p < 0.05$).Application of N_{100} increased reducing sugar up to 3.14%, crude protein up 3.14%, ascorbic acid up to 5.48% compared with the unfertilized control N_0. The treatment also led to a decrease of 0.18% in specific gravity, 2.77% in starch, 2.81% in dry matter and 5.08% in crude ash content versus to the non-fertilized control N_0. P_{100} application led to an increase of 7.79% in crude protein and 8.14% in vitamin C. The treatment also resulted in a decrease of 0.55% in specific gravity, 8.51% in starch, 8.64% in dry matter; 7.98% in reducing sugars and 10.74% in crude ash content versus to the non-fertilized control P_0. Application of K_{50} increased specific gravity up to 0.46%, starch up to 6.47%, dry matterup to 6.38%, crude protein up to 7.05%, ascorbic acid up to 6.82% compared with the unfertilized control K_0. The treatment also led to a decrease of 6.84% in reducing sugar content and 6.72% in crude ash content versus to the non-fertilized control K_0.

Table 4.27 Main effect of location, season, Nitrogen, Phosphorus and Potassium on potato quality attributes (on pooled basis [$L_{1\&2}$])

		SG	ST (%)	DM (%)	RS (%)	PRT (%)	VTC (mg/100g)	Ash(%)
N	0	1.090 ± 0.00[a]	15.89 ± 0.17[a]	21.35 ± 0.22[a]	0.223 ± 0.00[c]	1.59 ± 0.02[b]	21.00 ± 0.23[c]	1.18 ± 0.01[a]
	50	1.088 ± 0.00[b]	15.58 ± 0.18[b]	20.93 ± 0.24[b]	0.227 ± 0.00[b]	1.63 ± 0.02[a]	21.87 ± 0.25[b]	1.15 ± 0.01[b]
	100	1.088 ± 0.00[b]	15.45 ± 0.17[b]	20.75 ± 0.24[b]	0.230 ± 0.00[a]	1.64 ± 0.02[a]	22.15 ± 0.23[a]	1.12 ± 0.01[c]
LSD		0.0008	0.15	0.21	0.003	0.22	0.22	0.01
P	0	1.091 ± 0.00[a]	16.10 ± 0.15[a]	21.64 ± 0.21[a]	0.238 ± 0.00[a]	1.54 ± 0.02[b]	20.64 ± 0.23[c]	1.21 ± 0.01[c]
	50	1.091 ± 0.00[a]	16.09 ± 0.15[a]	21.61 ± 0.20[a]	0.222 ± 0.00[b]	1.65 ± 0.02[a]	22.05 ± 0.25[b]	1.16 ± 0.01[b]
	100	1.085 ± 0.00[b]	14.73 ± 0.18[b]	19.77 ± 0.24[b]	0.219 ± 0.00[c]	1.66 ± 0.02[a]	22.32 ± 0.23[a]	1.08 ± 0.01[a]
LSD		0.0008	0.15	0.21	0.003	0.02	0.22	0.01
K	0	1.087 ± 0.00[b]	15.15 ± 0.15[b]	20.36 ± 0.20[b]	0.234 ± 0.00[a]	1.56 ± 0.01[b]	20.96 ± 0.20[b]	1.19 ± 0.01[b]
	50	1.092 ± 0.00[a]	16.13 ± 0.13[a]	21.66 ± 0.17[a]	0.218 ± 0.00[b]	1.67 ± 0.01[a]	22.39 ± 0.18[a]	1.11 ± 0.01[a]
LSD		0.0006	0.13	0.17	0.002	0.01	0.18	0.009
Location	1	1.089 ± 0.00[b]	15.54 ± 0.14[b]	20.75 ± 0.19[b]	0.221 ± 0.00[b]	1.61 ± 0.01[b]	21.57 ± 0.20[b]	1.15 ± 0.01[b]
	2	1.090 ± 0.00[a]	15.74 ± 0.14[a]	21.26 ± 0.19[a]	0.232 ± 0.00[a]	1.62 ± 0.01[a]	21.77 ± 0.20[a]	1.16 ± 0.01[a]
LSD		0.0006	0.13	0.17	0.002	0.01	0.18	0.009
Season	1	1.089 ± 0.00	15.65 ± 0.14	21.02 ± 0.19	0.226 ± 0.00	1.62 ± 0.01	21.68 ± 0.20	1.15 ± 0.01
	2	1.089 ±0.00	15.63 ± 0.14	20.99 ± 0.19	0.226 ± 0.00	1.62 ± 0.01	21.67 ± 0.20	1.15 ± 0.01
LSD		0.0006	0.13	0.17	0.002	0.01	0.18	0.009
Mean		1.089	15.64	21.01	0.226	1.62	21.67	1.15
CV		0.25	3.47	3.51	4.15	3.48	3.53	3.55

Means followed by the same letter(s) within each column do not differ statistically (p= 0.05).

SG: Specific Gravity; ST: Starch; DM: Dry Matter; RS: Reducing Sugar; PRT: Protein, VTC: Vitamin C.

Interaction effect of location, season, Nitrogen, Phosphorus and Potassium on potato quality attributes on pooled basis

The results revealed that the interaction effects of location ×season × N× P× K, location × N× P× K and season × N× P× K on potato quality attributes (specific gravity, starch, dry matter, reducing sugars, protein, ascorbic acid and ash content)were not significant ($p > 0.05$).The analysis revealed also that the effects of N× P× K interaction were significant ($p < 0.05$) on specific gravity, starch, dry matter (Appendices 5 and 8), reducing sugar, crude protein, ascorbic acid and crude ash content. The results of analysis of variance on pooled basis for the interaction effects of N, P and K are displayed by Table 4.2. The treatment combination $N_{100}P_{100}K_{50}$ recorded the highest crude protein and ascorbic acid content. Application of$N_{100}P_{100}K_{50}$ treatment combination increased crude protein by 22.91% and ascorbic acid by 26.55% compared with the non-fertilized control $N_0P_0K_0$. The treatment combination decreased crude ash content by 23.07% versus to the control $N_0P_0K_0$. $N_0P_0K_{50}$ treatment combination recorded the highest specific gravity, starch and dry matter content. It increased specific gravity up to 0.64%, starch up to 8.74% and dry matter up to 8.68% versus to the non-fertilized control $N_0P_0K_0$. Compared with $N_{100}P_{100}K_{50}$ treatment combination which recorded the highest tuber yield, $N_0P_0K_{50}$ treatment combination led to an increase of 0.73% in specific gravity, 10.65% in starch, and 10.88%in dry matter. The treatment combination $N_{100}P_0K_0$ recoded the highest reducing sugar content. It increased reducing sugar content by 8.47% compared with the non-fertilized control $N_0P_0K_0$; the treatment combination also caused an increase of 18.52% in reducing sugar content versus to $N_{100}P_{100}K_{50}$ treatment combination which recorded the highest potato tuber yield.

Processing industries require potatoes with specific characteristics (mostly specific gravity, starch, dry matter and reducing sugars) which allow them to produce products of high quality. With regard to the highlighted specific traits, the results of ANOVA on pooled basis revealed that 83.33% of treatment combinations (NPK) produced tubers with > 1.080, > 14%, > 20% and < 0.30% of specific gravity, starch, dry matter and reducing sugar content, respectively. On the contrary, only tubers of $N_{100}P_{100}K_0$, $N_{50}P_{100}K_0$ and $N_0P_{100}K_0$ treatment combinations had < 1.080, < 14% and < 20% of specific gravity, starch and dry matter content, respectively.

Table 4.28 Interaction effect of Nitrogen, Phosphorus and Potassium on potato quality attributes (on pooled basis [$L_{1\&2}$])

Treat	SG	ST (%)	DM (%)	RS (%)	PRT (%)	VTC(mg/100g)	Ash (%)
$N_0P_{100}K_{50}$	1.088 ± 0.00^{f}	15.40 ± 0.36^{f}	20.67 ± 0.48^{f}	0.203 ± 0.01^{h}	1.64 ± 0.04^{cd}	21.70 ± 0.51^{cde}	1.10 ± 0.03^{h}
$N_0P_{50}K_{50}$	1.094 ± 0.00^{b}	16.59 ± 036^{b}	22.27 ±0.48^{b}	0.217 ±0 .01^{f}	1.67 ± 0.04^{bc}	22.09 ± 0.50c	1.16 ± 0.03^{de}
$N_{50}P_{100}K_{50}$	1.088 ± 0.00^{f}	15.40 ± 0.36^{f}	20.67 ± 0.49^{f}	0.209 ± 0.01^{g}	1.75 ± 0.03^{a}	23.72 ± 0.43^{a}	1.02 ± 0.04^{i}
$N_{100}P_{50}K_{50}$	1.093± 0.00^{bc}	16.39 ± 0.36^{bc}	22.00 ± 0.49^{bc}	0.217 ± 0.01^{f}	1.68 ± 0.04^{bc}	22.65 ± 0.50^{b}	1.11 ± 0.03^{gh}
$N_{50}P_{50}K_{50}$	1.093 ± 0.00^{bc}	16.34 ± 0.37^{bc}	21.94 ± 0.49^{bc}	0.216 ± 0.01^{f}	1.69 ± 0.04^{b}	22.67 ± 0.53^{b}	1.15 ± 0.03^{ef}
$N_{100}P_{100}K_{50}$	1.088 ± 0.00^{f}	15.40 ± 0.36^{f}	20.67 ± 0.48^{f}	0.216 ± 0.01^{f}	1.77 ± 0.04^{a}	24.02 ± 0.60^{a}	1.00 ± 0.03^{i}
$N_0P_{50}K_0$	1.090 ± 0.00^{de}	15.84 ± 0.37^{de}	21.27 ± 0.50^{de}	0.223 ± 0.01^{e}	1.59 ± 0.04^{ef}	21.05 ± 0.50^{fgh}	1.20 ± 0.03^{c}
$N_{50}P_{50}K_0$	1.090± 0.00^{def}	15.74 ± 0.39^{def}	21.14 ± 0.52^{def}	0.231 ± 0.01^{bcd}	1.64 ± 0.04^{cd}	21.97 ± 0.51cd	1.19 ± 0.03^{cd}
$N_{50}P_{100}P_0$	1.080 ± 0.00^{h}	13.75 ± 0.52^{h}	18.48 ± 0.71^{h}	0.227 ± 0.01^{de}	1.61 ± 0.04^{def}	21.55 ± 0.53^{def}	1.14 ± 0.03^{efg}
$N_0P_{100}K_0$	1.085 ± 0.00^{g}	14.80 ± 0.36^{g}	19.86 ± 0.48^{g}	0.232 ± 0.01^{bcd}	1.58 ± 0.04^{f}	20.93 ± 0.51^{gh}	1.14 ± 0.03^{ef}
$N_{100}P_{100}K_0$	1.079 ± 0.00^{h}	13.63 ± 0.44^{h}	18.29 ± 0.59^{h}	0.228 ± 0.01^{cde}	1.63 ± 0.04^{c}	22.05 ± 0.50^{cd}	1.13 ± 0.03^{fg}
$N_{100}P_{50}K_0$	1.089 ± 0.00^{ef}	15.62 ± 0.35^{ef}	21.05 ± 0.49^{def}	0.232 ± 0.01^{bcd}	1.62 ± 0.04^{de}	21.88 ± 0.52^{cd}	1.17 ± 0.03^{de}
$N_{50}P_0K_{50}$	1.094 ± 0.00^{b}	16.57 ± 0.29^{b}	22.29 ± 0.39^{b}	0.230 ±0.01^{bcd}	1.63 ± 0.04^{de}	21.80 ± 0.52^{cd}	1.16 ± 0.03^{de}
$N_0P_0K_{50}$	1.096 ± 0.00^{a}	17.04 ± 0.40^{a}	22.92 ± 0.54^{a}	0.228 ± 0.01^{cde}	1.61 ± 0.04^{def}	21.26 ± 0.50^{efg}	1.20 ± 0.03^{c}
$N_{100}P_0K_{50}$	1.091 ± 0.00^{cd}	16.04 ± 0.37^{cd}	21.52 ± 0.50^{cd}	0.233 ± 0.01^{bc}	1.60 ± 0.04^{ef}	21.61 ± 0.52^{cde}	1.14 ± 0.03^{efg}
$N_0P_0K_0$	1.089 ± 0.00^{de}f	15.67 ± 0.37^{def}	21.09 ± 0.50^{def}	0.236 ± 0.01^{b}	1.44 ± 0.05^{h}	18.98 ± 0.61^{j}	1.30 ± 0.03^{a}
$N_{50}P_0K_0$	1.089 ± 0.00^{def}	15.67 ± 0.37^{def}	21.07± 0.52^{def}	0.250 ± 0. 00^{a}	1.45 ± 0.06^{h}	19.52 ± 0.74^{i}	1.27 ± 0.02^{b}
$N_{100}P_0K_0$	1.089 ± 0.00^{ef}	15.64 ± 0.37^{ef}	20.97 ± 0.49^{ef}	0.256 ± 0.01^{a}	1.53 ± 0.04^{g}	20.70 ± 0.50^{h}	1.18 ± 0.03^{cd}
Mean	1.089	15.64	21.01	0.226	1.62	21.67	1.15
LSD	0.003	0.54	0.73	0.009	0.04	0.53	0.03
CV	0.25	3.47	3.51	4.15	3.48	3.53	3.55

Means followed by the same letter(s) within each column do not differ statistically (p= 0.05).

SG: Specific Gravity; ST: Starch; DM: Dry Matter; RS: Reducing Sugar; PRT: Protein, VTC: Vitamin C.

CHAPTER FIVE
DISCUSSION

5.1 Soil characterization

5.1.1 Soil physical and chemical characterization

The results revealed the variability of selected soil physical and chemical properties between farm plots as well as between locations (AEZs). Bulk density affects infiltration, rooting depth/restrictions, available water capacity, soil porosity, plant nutrient availability, and soil microorganism activity, which influence key soil processes and productivity. The variability of bulk density depicted the variability of minerals and organic matter content. All recorded values of bulk density were less than the general critical value (< 1.80 gcm^{-3}) for plant growth at which roots penetration is likely to be severely restricted (Brady and Weil, 2008). According to Bruce and Rayment (1982) [Appendix 11], soil pH ranging from 5.50 to 6.00 and from 6.00 to 6.50 are considered as moderately acidic and slightly acidic, respectively. Thus, soil pH of the study areas varied from moderately acidic to slightly acidic. The acidic pH observed in the research locations might be as a result of the leaching of basic cations owing to high rainfall and incessant uptake of cations by crop. The supply of plant nutrients and thus, the fertility of the soil are affected by pH as the solubility of most nutrients varies in response to pH. However, the depicted acidity range of the soils in the study sites implied that nutrients are likely to be available for crop uptake (Yihenew *et al.*, 2015).

According to ratings given by Landon (1991), soil organic carbon (OC) ranging from 2.00% to 4.00% is categorized as low while soil OC ranging from 4.00% to 10.00% is classified as medium [Appendix 12]. According to indices of the same author, total nitrogen (TN) ranging from 0.10 % to 0.20% is considered as low while TN varying from 0.20 % to 0.50 % is classified as medium [Appendix 12]. Therefore, soil OC and total N of the study areas varied from low to medium. Both ratings of soil OC and TN may be attributed to complete or excessive exportation (removal) of vegetative biomass from the farm during harvesting process, limited use of organic inputs, high level of organic matter mineralization and leaching process of NO^{-3} anions (Laekemariam, 2015). According to Landon (1991) classification, available P of all soil samples of the study locations is classified as medium (5.00 ppm-15.00 ppm) [Appendix 12]. This medium class of available P rating can be explained by the presence of acidic pH, limited P fertilizer application and its continuous mining from the field (Laekemariam, 2016). According to Landon (1991) indices, soil Ca content less than 4.0 meq/100g is considered as low while it is qualified as medium when ranging from 4.0 meq/100g to 10.0 meq/100g; soil Mg content less than 0.50 meq/100g is qualified as low whereas it is considered as medium when ranging from 0.50 meq/100g to 4.00 meq/100g [Appendix 12].The same author also qualified Na content ranging from 0.10 meq/100g to 0.30 meq/100g as low; K content ranging from 0.20 meq/100g to 0.60 meq/100g and Na content fluctuating from 0.30 meq/100g to 0.70 meq/100g as medium. Furthermore, CEC ranging from 5.00 meq/100g to 15.00 meq/100g was qualified as low whereas CEC varying from 15.00 meq/100g to 25.00 meq/100g was qualified as medium. BS ranging from 20.00% to 60.00% was classified as medium, BS greater than 60.00% was considered as high [Appendix 12]. Using these reference points, the concentration of exchangeable bases, Na, CEC and BS of the study areas were in general either low or medium. The low to medium concentration of exchangeable bases, Na, CEC and BS can be attributed to the soil parental material properties, leaching of bases (cations), continuous removal of the bases by crops and low use of organic inputs (Bezabih *et al.*, 2016).

According to Landon (1991) rating, S content fluctuating from 6.00 ppm to 10.00 ppm is considered as medium [Appendix 12]. Therefore, S content in the study locations was medium; this can be related to organic carbon content varying from low to medium which also may have resulted from soil organic matter content relatively low, limited use of external S fertilizers, soil acidity and its uptake by crops (Laekemariam, 2016). According to Landon (1991), variation classes of (0.30-0.80) ppm, (4.00-6.00) ppm, (1.20-3.50) ppm and (1.00-3.00) ppm for Cu, Fe, Mn, and Zn, respectively are qualified as medium; (3.51-6.00) ppm for Mn and (0.51-1.00) ppm for Zn are considered as high and low, respectively [Appendix 12]. In general micronutrient content in the study areas varied from low to medium. The observed low to medium content of soil micronutrients in the research areas may be attributed to low-medium soil organic matter (SOM) ratings which had led to low-medium ratings of OC. In fact, there is a relationship between SOM and micronutrients content. Deficiency of micronutrients is expected to occur in areas with low soil organic matter content. Usually, the greater the content of active (not lignified) SOM, the more the availability of micronutrients. This is due to the release of the micronutrients through decomposition of SOM and chelating compounds. Their availability may also be due to their release from organic complexes (Brady and Weil, 2002; Nazif *et al.*, 2006).

In general, soil fertility ratings were mainly low or medium. The research results confirm the findings of Bationo *et al.* (2007) and Sanginga and Woomer (2009) revealing that most Africans soils are inherently poor or degrading and have low OC, nutrients levels, CEC and bases saturation. The results of the present research are in accordance with the findings of Bucagu *et al.* (2013) and Franke *et al.* (2016) revealing that in Rwanda, soil properties vary spatially from a field to a larger region scale. They are also in conformity with research results of Tittonell *et al.* (2010) highlighting heterogeneity in soil fertility between farms. According to Bucagu *et al.* (2013) and Franke *et al.* (2016), spatial variability of soil fertility is influenced by both intrinsic (soil formation factors, such as soil parent materials and catenal position) and extrinsic factors (soil management practices, farming systems, socio-economic factors, farm size and location, etc.)

Variability in soil fertility can occur at different scales, including field level land use, distance of fields from the homestead, and among households (Vanlauwe *et al.,* 2006; Tittonell *et al.,* 2007). In the same line, it was also indicated that rates of change in soil nutrient stocks in Sub-Saharan Africa may vary from one farm to another and land plot to another in the same farm (Zingore *et al.*, 2007; Zingore *et al.*, 2011). It was also observed that smallholder farmers having insufficient fertilizers, use them particularly on farm plots neighboring their homesteads. The scenario lead to a steep gradient of increasing fertility of soil with decreasing distance from the farmhouse (Zingore *et al.*, 2011). Such allocation of nutrient resources, coupled with inherent spatial heterogeneity in soil fertility results in steep gradient of soil fertility between farms and even farm plots subjected to imbalanced nutrient supply. Zingore *et al.* (2007)also indicated the presence of prominent gradient of soil fertility generated by different agricultural practices even on small plots of land closer to farmhouses. This spatial heterogeneity in soil fertility within and between farms affects resource use efficiencies, crop yield and quality (Tittonell *et al.*, 2008). Allocating nutrient resources on more fertile homefields than on depleted outfields culminates in a new scenario of eternizing spatial heterogeneity in soil fertility at small, medium and large scales (Zingore *et al.*, 2007). With regard to soil chemical properties, generally, Mudende location exhibited higher values than Rwerere location in nearly all soil chemical parameters tested, Mudende was more fertile than Rwerere.

5.1.2 Correlation and factor analysis on soil properties

The study revealed that properties like organic carbon (OC) and pH are shapers and more indicative of soil fertility status, it was also depicted by analysis of correlation coefficient associating them with other soil parameters.

Relationship between soil organic carbon and other soil properties

With regard to the positive relationship between SOC and soil pH, it is emphasized that the effect of organic matter (as source of OC) on soil pH is dependent on the chemical properties of the soil and the organic material itself. In general, incorporation into acidic soil, of mature organic input (with a neutral to slightly alkaline pH), is expected to increase its pH (Andersson *et al.* 2000). An increase of soil pH following addition of organic amendment is mainly due to addition of basic cations, ammonification and production of NH_3 during decomposition (Hubbard *et al.*, 2008). Additionally adsorption of H^+ ions, development of reducing conditions due to increased microbial activity and displacement of hydroxyls from sesquioxide surfaces by organic anions can lead to pH increase in soils amended with organic materials (Duong, 2013). Soil organic matter (source of OC) is known to decrease bulk density because of its positive effect on abundance of soil pores and its tendency to increase porosity by aggregating soil particles. The results are in accordance with those of Sakin (2012) and Herencia *et al.* (2011). The significant and positive relationship between OC and TN could be because of release of mineralizable nitrogen from soil organic matter in proportionate amounts (Vanilarasu and Balakrishnamurthy, 2014), and adsorption of NH_4^+ by humus complexes in soil. The results are in conformity with those of Kumar *et al.* (2014). The significant and positive correlation between OC and available phosphorus might be due to the formation of easily accessible organophosphate complexes, release of phosphorus from organic complexes and reduction in phosphorus fixation by humus due to formation of coatings on iron and aluminum oxides. The results are in harmony with the findings of Ayele *et al.* (2013) and Singh *et al.* (2014).

The increase in availability of S by organic OC may be attributed to release of S from organic complexes through mineralization. Similar results were reported by Pareek (2007) and Basumatari *et al.* (2010). Organic carbon showed a positive association with cation bases (Ca, Mg, and K), CEC and base saturation (BS). In fact, increase in OC arises from incorporation and decomposition of organic matter. Organic amendments act as nutrients reserve, have high negative charges and CEC, and can increase soil bases holding capacity, CEC and BS when incorporated. Humic acids, the major components of organic amendments, can bind cations because they contain carboxylic acid groups, which can bind positively charged ions (Pedra *et al.*, 2008). There was significant and positive relationships between organic carbon and micronutrients (Cu, Fe, Mn and Zn). The micronutrient cations react with certain organic molecules to form organometallic complexes as chelates and soluble chelates can increase the availability of the micro- nutrients and protect them from precipitation reactions. Moreover, their availability maybe due to their release from organic complexes (Brady and Weil, 2002). Soils with good organic matter content have high micronutrient availability due to formation of soluble chelates and prevention of macronutrient cations from fixation, precipitation, oxidation and leaching (Babu *et al.*, 2007). The results are in harmony with findings of Verma *et al.* (2007), Jiang *et al.* (2009) and Bassirani *et al.* (2011).

Relationship between soil pH and other soil properties

An increase in pH leads to an increase in organic matter solubility(Andersson *et al.* 2000). The increase in soil OC may be due to high population of decomposers and accelerated rate of decomposition of organic matter owing to increased biological activity associated with increased pH (Kumar *et al.*, 2014). Regarding the association of soil pH with bulk density, it was found that the bulk density was not directly correlated with pH. However, the correlation may be induced by existence of positive correlation between pH and OC where increase of soil pH resulted in increase of organic matter solubility and increase of OC content in the soil. The latter increases the total volume of pore spaces which leads to bulk density decrease. The results are in harmony with findings of Sakin (2012). Soil pH was positively associated with total nitrogen (TN). In fact, soil pH affects directly the kind, density and the activity of fungi, bacteria and actinomycetes involved in the process of decomposition and thereby rate of decomposition of organic matter. The increase in availability of N may be due to accelerated rate of decomposition and mineralization of organic matter owing to increased biological activity. The results are in accordance with the findings of Kumar *et al.* (2014). The results revealed a positive association between soil pH and available phosphorus. This was due to relatively indirect effect of pH through organic matter indicating the influence of pH on soil organic matter decomposition and direct contribution of soil organic matter to available P through mineralization of organic matter. Also, low pH (< 5.5) and high (> 7.5) limits P-availability to plants due to fixation by aluminum, iron, or calcium. The results are in conformity with the findings of Kumar *et al.* (2014). Soil pH is an important soil parameter which is positively correlated with exchangeable bases, CEC and BS, thereby high pH values increase numbers of negative charges, which attract and hold cations, on the colloids. Indeed, increased soil pH results in increased capacity of soil colloid to hold cation bases, high CEC and base saturation (Kumar *et al.*, 2014).

The significant positive correlation between soil pH and available S was due to indirect effect of pH through organic matter reflected by the influence of pH on soil organic matter decomposition and direct contribution of soil organic matter to available sulphur through mineralization. The observation was supported by the results of research done by Medhe *et al.* (2012) and Paritosh *et al.* (2012). There was significant positive association between pH and micronutrients (Cu, Fe, Mn and Zn). The association may be indirect through a direct effect of organic matter on micronutrients availability. Their availability maybe due to their release from organic complexes (Brady and Weil, 2002), formation of soluble chelates and prevention of those micronutrient cations from fixation, precipitation, oxidation and leaching (Babu *et al.*, 2007). The correlation might also be due to leaching losses of water soluble micronutrients with the high rainfall leading to their low content in the more acidic soils as they are most soluble under more acidic condition. The results are in harmony with findings of Verma *et al.*(2007), Jiang *et al.* (2009) and Bassirani *et al.* (2011).

Factor analysis on soil properties

At both locations, Mudende (L_1) and Rwerere (L_2), the first factor was named "organic carbon driven" because OC loaded better on the factor 1 and has substantial influence on other variables reflected by the same latent factor whereas the second one was named "CEC driven" due to the fact that CEC loaded better on factor 2 and has greater influence on other variable depicted by the same latent factor. "Organic carbon driven" factor is related to “dynamic soil properties”; soil features which are responsive to current or recent management decisions on the human time scale (Tugel *et al.*, 2008; Wienhold *et al.*, 2004) whereas "CEC driven factor" is related to “inherent soil properties”; soil attributes which are mainly determined by basic soil forming factors and relatively unresponsive to recent management (Tugel *et al.* 2008; Brady and Weil, 2002). However, some of “inherent properties”, such as CEC, can be influenced by other properties, such as nature and percentage of clay and soil organic matter (Tugel *et al*,. 2008).

With regard to the factor 1 ("organic carbon driven" factor), the latent factor underlying observed variables can be qualified dynamic soil quality component. The component is reflected by dynamic soil properties such as pH, organic matter (SOM) and organic carbon (OC), microbial community, bulk density, infiltration rate, soil water, and nutrient holding capacity (Al-Kaisi and Kwaw-Mensah, 2017; Wienhold *et al.*, 2004). With respect to the factor 2 ("CEC driven" factor), the latent factor underlying observed variables can be qualified as inherent (intrinsic or static) soil quality component. This second soil quality component is reflected by inherent soil properties such as soil texture and mineralogy, depth to bedrock, drainage class, and cation exchange capacity (CEC) (Brady and Weil, 2002;Al-Kaisi and Kwaw-Mensah, 2017). The results are in accordance with findings of Carter (2002) revealing that soil quality encompasses two general points of view: (1) the inherent properties of a soil, defining an innate capacity of any soil to function; (2) the dynamic nature of a soils to function as influenced by human use and management decisions.

5.2 Effect of Nitrogen, Phosphorus and Potassium on potato growth, yield and yield components

5.2.1 Potato growth, yield and yield components

When roots grow in an environment, copiously supplied with water and nutrients, they produce additional root hairs and root surface area of absorption is increased. Such a situation results in high growth of potato (Kumari, 2012). This could have been the case in the present study since single site ANOVA and ANOVA on pooled basis revealed that the main effects of location, season, N, P, K and interaction effects N × P × K were significant on stem height, leaf area index and tuber yield. High growth was manifested in the establishment of a taller stem height and a larger leaf area index. Both growth characteristics should have resulted from a vigor root system, well developed and properly established owing to adequate supply of nutrients. Early root growth and establishment enable faster stem growth rates since there is greater capture of other nutrients resulting from increased root surface area of absorption (Boyd *et al.*, 2002). Taller plants with a vigorous root system and higher leaf area index lead to high interception of solar radiation, mainly due to the greater photosynthetic surface area of the crop. Such a situation result from increased photosynthetic capacity and supply of the assimilates which in turn lead to increased stem growth and leaf expansion (Jenkins and Mahmood, 2003).

Increase in growth and yield normally depends on increase in the dry mass of plants which depends on the amount of photoassimilates fixed through photosynthesis (Geremew *et al.*, 2007). In this study, plants treated with higher levels of N, P and K (N_{100}, P_{100} and K_{50}) and their combination ($N_{100}P_{100}K_{50}$) were taller and presented larger leaf area index. The two growth characteristics should have resulted from a vigorous root system that was well developed and properly established owing to suitable supply of nutrients. Taller plants with a vigorous root system and larger leaf area index lead to higher photosynthesis rate resulting in good translocation and storage capacity, worthy tubers induction and initiation, tubers swelling and then big and high number of tubers leading to high tuber yield (Jenkins and Mahmood, 2003; Kumari, 2012). Low levels of mineral nutrient restrict stem elongation, leaf area expansion and photosynthetic capacity, stolon initiation, tuber bulking rate, duration of tuber bulking and tuber weight as well (Geremew *et al.*, 2007). Maximum tuber growth rate requires a healthy canopy, supplied with essential nutrients at optimal rates. Tuber bulking rates can be reduced by deficit fertilizer applications. In this case, canopy growth is limited and canopy duration is shortened by nutrient deficiency, this results in reduced carbohydrate production-translocation and consequently tuber growth rates (Jenkins and Mahmood, 2003). Shorter potato stems, lower LAI obtained from N_0, $P_0$and K_0 and their combination ($N_0P_0K_0$) indicated that less assimilates were available for crop growth and consequently lower tuber bulking and yields. This suggests that not enough assimilates were supplied by the source to meet the demands of growing sink tubers, and potato yield was limited mainly by the source capacity.

The results of the present research are in agreement with the findings of other researchers who found that increasing N levels resulted in significant increase of stem height and leaf area index (Mulubrhan, 2004 and Zelalem *et al.*, 2009). According to results of research works of other authors, increasing P levels significantly increased stem height (Mulubrhan, 2004; Zelalem *et al.*, 2009) and leaf area index (Allison *et al.*, 2001). The research's results are in harmony with the research conclusions which highlighted significant increase in stem height (Daniel *et al.*, 2016) and LAI (Marton, 2001; Saha *et al.*, 2001) due to progressive application of different K levels.

The presence of positive association between number of tubers per plant N rate can be attributed to an increase in stolon number through N effect on gibberellins biosynthesis in the potato plant. N rate influences formation of potato tubers by influencing the activity and equilibrium of phytohormones (particularly gibberellic, abscissic acids and cytokinins) in the plant (Alemayehu *et al.*, 2015). In this study, a significant increment in tuber number was observed in response to N application; this is in agreement with results reported by various authors (Guler, 2009; Zelalem *et al.*, 2009; Zamil *et al.*, 2010; Zabihi-e-Mahmoodabad *et al.*, 2011; Zewide *et al.*, 2012). The average fresh tuber weight progressively increased with increasing nitrogen rate. In agreement with the present findings, Mulubrhan (2004), Guler

(2009), Zewide *et al.* (2012) and Jamaati-E-Somarin *et al.* (2010), reported a significant increase in average fresh tuber weight in response to nitrogen application. Moreover, increasing rate of nitrogen increased marketable tuber (medium and large size) yield and total tuber yield. Similarly, Mulubrhan (2004), Zelalem *et al.* (2009), Guler (2009) and Zamil *et al.* (2010) reported significant increase in marketable and total tuber yield in response to increased level of nitrogen application. On the contrary, small size and unmarketable tuber yield decreased with increasing N rates. The results are in agreement with the findings of other researchers who found that increasing nitrogen levels resulted in significant increase of marketable (medium and big size) tuber yield at the expense of small size and unmarketable tuber yield. The reduction in yield of small size and unmarketable tuber yield due to gradual increase of N rate may be associated with the increment of both marketable and total tuber yield (Jamaati-E-Somarin *et al.*, 2010; Alemayehu *et al.*, 2015; Birtukan, 2016). Agronomic Efficiency (AE) of N was significant ($p < 0.05$) and was decreased with increasing rate of N. The trend of variation is due to the fact that input-output (N rate and tuber yield) relationship follows the law of diminishing return. The results are in accordance with the findings of different authors (; Kumar *et al.*, 2009; Trehan, 2009; Mozumder *et al.*, 2014; Das et *al.,* 2015 and Tsegaye, 2017) indicating that agronomic nitrogen use efficiency decreased with every incremental dose of Nitrogen.

The number of tubers per plant was found to increase with increasing phosphorus rate. The results are in accordance with the findings of Mulubrhan (2004), Rosen and Bierman (2008) and Zewide *et al.* (2012) who reported that increasing phosphorus application increased number of tubers per plant. The average tuber weight gradually increased with increasing phosphorus rate. The results are consistent with the findings of other authors (Mulubrhan, 2004; Zelalem *et al.*, 2009; Zewide *et al.*, 2012) who reported that increasing phosphorus rate application increased fresh mean tuber weight. Furthermore, increasing rate of phosphorus, increased marketable tuber (medium and large size) yield and total tuber yield. Similarly, Allison *et al.* (2001), Mulubrhan (2004), Zelalem *et al.* (2009) and Zewide *et al.* (2012) reported significant increases in marketable and total tuber yield in response to increased level of phosphorus application. As was the case with N, small size and unmarketable tuber yield decreased while P rate was increased. Deficiency of P nutrient may have decreased the growth above ground biomass and tuber growth, leading to reduced tuber size, then high small and unmarketable tuber yield. Unmarketable tuber yield reduction due to progressive increase of P rate may be associated with the increment of both marketable and total tuber yields. Other authors also proved that increasing phosphorus levels resulted in significant increase of marketable (medium and big size) tuber yield at the expense of small size and unmarketable tuber yield (Birtukan, 2016; Nebiya, 2016; Girma *et al.*, 2017). In addition, AE of P was very significant ($p < 0.05$) and followed also the law of diminishing return as far as the relationship between P fertilizer rate and yield was concerned. Potato crops utilized P highly for their physiological functions and processes when P was at lower levels than higher levels. This might be due to the allocation of more absorbed P to their underground part, mainly tuber, which increased the production of tuber dry matter than the above ground parts, which might be higher at higher rates of P. Similarly, Fernandes and Soratto (2012) found that as lower levels of P was applied, shoot dry matter reduced drastically, while more P was allocated in roots to ensure growth. Similar findings on agronomic efficiency of P were reported by other researchers (Trehan, 2009 and Sandana, 2016) who showed that AE of P decreased when P rate increased.

There was a positive association between number of tubers per plant and potassium rate. The present results are in agreement with findings of other authors (Adhikary and Karki, 2006; Bansal and Trehan, 2011; Habtam, 2012; Wibowo *et al.*, 2014; Debashis, 2015; Zelelew *et al.*, 2016; Kumar *et al.*, 2017). The average fresh tuber weight progressively increased with increasing phosphorus rate. In agreement with the present findings, Moinuddin *et al.* (2004), Adhikary and Karki (2006), Bansal and Trehan (2011), Wibowo *et al.* (2014), Debashis (2015) and Zelelew *et al.* (2016) have reported the presence of a positive association between average potato weight and potassium rate application. Furthermore, increasing potassium levels resulted in significant increase of marketable (medium and big size) and total tuber yield at the expense of small size and unmarketable tuber yield. Increase in total yield and the yield of medium and large tubers due to K fertilization may stem from the stimulating effect of potassium on photosynthesis, phloem loading and translocation as well as synthesis of large molecular weight substances within storage organs contributing to the rapid and effective bulking of the tubers (Singh and Lal, 2012). Small size and unmarketable tuber yield reduction due to gradual increase of K rate may be associated with the increment of both marketable and total tuber yield (Umar and Moinuddin, 2001; Adhikary and Karki, 2006; Bansal and Trehan, 2011; Wibowo *et al.*, 2014; Zelelew *et al.*, 2016). The present results also corroborate with the findings of other authors (Moinuddin *et al.*, 2004; Habtam, 2012; Wibowo *et al.*, 2014; Debashis, 2015; Kumar *et al.*, 2017) who reported that progressive application of K significantly increased the aggregate (total tuber yield) as well as marketable (large and medium grade) tuber yield with concomitant decrease in the yield of small grade and unmarketable tuber yields.

The present research findings are also in harmony with findings of Nava *et al.* (2007), Ram (2009) and Muhammad *et al.* (2015) who stated that effects of N × P × K on potato growth attributes (stem height and leaf area index), tuber yield and yield attributes were significant and potato productivity increased with increasing rate of nutrients up to a certain level while the control treatment being the least productive. Birtukan (2016) also indicated that the increase in the number of tubers per plant, mean tuber weight, medium and large size tuber yield and aggregate tuber yield with the supply of fertilizer nutrients could be due to more luxurious growth, more foliage and leaf area and higher supply of photosynthesis. Nitrogen, phosphorus and potassium deficiency contributed to the development of small tubers due to scarcity of photoassimilates for tuber enlargement and bulking (Burga *et al.*, 2014). Thus, N, P and K deficiency may have extremely enhanced the small and unmarketable tuber numbers and yields at the lowest and marginal levels of N, P and K supply. Therefore, it could be suggested that marketability of potato tubers could be improved through enhanced N, P and K application.

The response of N, P, K and N × P × K application on the number of main stems per plant was found to be non-significant. This could be due to the fact that the trait is much more influenced by the inheritance of the potato crop. In fact, the number of main stems per plant can be influenced by variety, seed tuber size, and physiological age of the seed, storage conditions, and number of viable sprouts at planting, sprout damage at the time of planting and crop management (Mulubrhan, 2004; Zelalem *et al.*, 2009). However, those factors were not used as variables during the present research work.

Higher agronomic efficiency values were observed with lower rates of Nitrogen (N_{50}) and Phosphorus (P_{50}). Agronomic efficiency decreased with every incremental dose of N and P, confirming the law of diminishing return (Barker and Pilbeam, 2006; Roy *et al.*, 2006). This trend of variation of N and P agronomic efficiency resulted from the relationship between input and output which follows the law of diminishing return (Das *et al.*, 2015). Nitrogen and phosphorus AE decreased with increasing N and P supply due to the existence of negative association between nutrient rate and agronomic nutrient efficiency (Trehan, 2009; Salam *et al.*, 2014). The results are in agreement with the findings of other authors (Darwish *et al.*, 2006; Kumar *et al.*, 2007; Fontes *et al.*, 2010; Sandana, 2016; Bekalo, 2017) illuminating that each additional unit of fertilizer nutrient gives slightly smaller benefit than the previous unit.

In general, effects of location and season on N and P and K agronomic efficiency were not statically significant, except for N_{50}. However, Mudende location recorded higher agronomic nutrient efficiency and responded better to fertilizer application than Rwerere location. The results are in accordance with the findings of Baligar *et al.* (2001) and Cui *et al.* (2014) who reported that improved soil environment enhances both water and nutrient efficiency. They stated that nutrient use efficiency is improved through optimizing crop-growing environment, mainly soil properties and weather conditions. In fact, Mudende location recorded higher values inpH, OC (reflecting organic matter content), TN, exchangeable bases, base saturation, available phosphorus and sulphur and macronutrients. Moreover, the location displayed also better soil texture and bulk density compared to Rwerere (Tables 4.1-4.3). All these soil properties contributed to higher agronomic efficiency owing to better soil aeration, water infiltration, water holding capacity, root penetration and growth, microbial processes, plant nutrients availability and absorption. The present results are also in line with research findings of Zebarth *et al.* (2004) and Bekalo (2017) revealing that agronomic nutrient efficiency depends primarily on crop variety and fertilizer nutrient rate, but soil properties, weather conditions and agronomic practices can also affect it. In addition, Mudende location was also characterized by low temperature and high daily temperature range, both characteristics are known hasten tuber induction and initiation, thereby lengthening tuber growth and bulking period; such a situation results in higher nutrient use efficiency and tuber yield (Struik, 2007; Gghulam, 2011).

Effects of location and season on potato growth, tuber yield and yield components were significant ($p < 0.05$). This was due to locational and seasonal differences in terms of soil quality (texture and fertility mainly) and weather features prevailing during the growth of the crop. According to Tisdale *et al.* (2003), factors affecting crop growth and yield (both in quantity as well as quality) can be categorized into four major headings: the genetic make-up of the crop, the soil upon which the crop grows, the climatic conditions during the growth of the crop, and the management practices, mainly soil fertility. Maintaining adequate levels of soil fertility has been recognized as one of the management practices that affect growth, development and yield of plants. According to Monteith (2000), for a crop free of pests and diseases, weather is the primary determinant of crop growth and yield. According to Rytel *et al.* (2013), the growth, yield and quality of potatoes *(Solarium tuberosum* L.) are strongly affected by soil fertility levels, genetics, weather conditions and chemical treatments that are applied. In fact, with regard to soil chemical properties of the research sites, Mudende exhibited higher values than Rwerere in nearly all soil chemical parameters tested; Mudende was more fertile than Rwerere (Tables 3.2, 4.1- 4.3).

According to André and Nilson (2008), meteorological factors directly influence crop potential productivities through regulating its transpiration, photosynthesis, dry matter partitioning and respiration processes in such a way as to control the growth and development of the plants throughout their physiological cycle at a given site. In the case of the present research, Mudende location was cooler, with higher differences between day and night temperatures (high daily temperature range) (Table 3.1). Similarly, season 2 (March-June 2017) was also characterized by cooler temperatures and higher daily temperature range compared with season 1 (September-December 2016). Both factors, low temperature and high daily temperature range, are known to delay crop development, but hasten tuber induction and initiation, thereby lengthening tuber growth and bulking period; such a situation results in medium and big sized tubers and higher tuber yield (Struik, 2007; Gghulam, 2011). On the contrary, high temperatures and narrow daily temperature range are inhibitory for tuberization. High temperatures affect the partitioning of assimilates by decreasing the partitioning to the tubers and increasing the partitioning to other parts of the plant while low temperatures, enhance tuber initiation, increase the number of tubers formed, allow longer periods of photosynthesis, enhance efficient translocation of assimilates from haulm to tubers and lower respiration rates during the cool nights, such conditions lead to medium and big sized tubers and higher tuber yield (Levy and Veilleux, 2007).

Another factor that brought differences between the two locations is soil texture: it was sandy loam and sandy clay loam at Mudende and Rwerere locations, respectively. It has been shown that well-drained soils with loamy sand to sandy loam textures are considered most suitable for potato production. These soils have an adequate capacity to retain water, provide sufficient aeration for root and tuber development and favourable conditions for planting and harvesting (Western Potato Council, 2003). Farmers may produce successfully potatoes on silt loam, sandy clay loam; silty clay loam and clay loam textural classes but these soils are not considered ideal for potato production. These finer texture soils are prone to water erosion in undulating landscapes, poor to fair internal drainage and soil clod formation if tilled when wet. A soil that contains a large amount of clay becomes sticky when wet and lumpy when dry. Such conditions may impede root growth, nutrients absorption, tubers growth and bulking, and lead to low tuber yield (Western Potato Council, 2003).

5.2.2 Relationships and principal component analysis for potato growth and yield attributes

Correlation between selected potato growth and yield attributes

The results of the present study depicted the existence of positive and significant association between aggregate tuber yield and all potato growth and yield parameters on which the study focused except the number of main stems per plant. The present findings are in conformity with the findings of other authors (Moinuddin and Bansal, 2005; Singh and Lal, 2012 ; Birtukan, 2016; Mishra *et al.*, 2018) who reported that aggregate potato tuber yield exhibited the positive and significant correlation with stem height, leaf area index, number of tubers per plant, fresh tuber weight, medium sized tuber yield, large sized tuber yield and marketable tuber yield. According to Moinuddin and Bansal (2005), Singh and Lal (2012) and Birtukan (2016), small and unmarketable tuber yield follow a reverse trend of variation compared to other yield traits. Similarly, small and unmarketable tuber yields had significant, but negative, correlation with total tuber yield. The correlation between number of main stems per plant and aggregate tuber yield was not significant. The results of this research are in harmony with the findings of Khayatnezhad *et al.* (2011), Felenji *et al.* (2011), (Darabad, 2014) and (Yousif *et al.*, 2015) which reported the non-existence of significant correlation between number of main stems per plant and aggregate potato tuber yield.

Regression between mineral fertilizer rates and tuber yield parameters

Analysis of multiple linear regression revealed occurrence of significant dependencies between dependent variables (number of tubers per plant, fresh tuber weight, small tuber yield, medium tuber yield, large tuber yield, unmarketable tuber yield and total tuber yield) and independent variables (N, P and K fertilizer rates). The results revealed that all dependent variables can be adequately either explained or predicted using independent variables.

Number of tubers per plant, fresh tuber weight, medium tuber yield, large tuber yield, marketable and total tuber yields responded in a positive way to nitrogen, phosphorus and potassium fertilizer application rates. Each increment on nitrogen, phosphorus and potassium fertilizer rate resulted in an increment of number of tubers per plant, fresh tuber weight, medium tuber yield, large tuber yield, marketable tuber yield and total tuber yield. The results obtained in the present investigation are in agreement with those obtained by Bélanger *et al.*

(2000), Gayler*et al.*(2002), Nava *et al.* (2007), Ram (2009), Fontes *et al.* (2010), Mona *et al.* (2012), Muhammad *et al.* (2015), Santos *et al.* (2018) and Nazli *et al.* (2018).

Small and unmarketable tuber yields responded in a negative way to nitrogen, phosphorus and potassium fertilizer application rates. Each increment on nitrogen, phosphorus and potassium fertilizer rate resulted in a reduction of small and unmarketable tuber yields. Alemayehu *et al.* (2015), Debashis (2015), Birtukan (2016), Girma *et al.* (2017) and Kumar *et al.* (2017) reported similar association between small and unmarketable tuber yields with nitrogen, phosphorus and potassium fertilizer rates application. On the other hand, the response of the number of main stems per plant to nitrogen, phosphorus and potassium fertilizer rates application was not statistically significant. Each increment on nitrogen, phosphorus and potassium fertilizer rate resulted in non-significant variation of the average number of main stems per plan. These findings are in line with the results of Mulubrhan (2004), Zelalem *et al.* (2009) and Mona e*t al.* (2012).

Agronomic optimum nutrient rate for potato

Application of optimum fertilizer rate is necessary to improve N use efficiency, crop yield and quality with low environmental health risk (Heckman, 2007). Bélanger *et al.* (2000) reported that the quadratic model is the best to display the fitted best to describe the response of crop yield to nitrogen fertilizer application and to identify optimum nitrogen rate.

The results of the present research showed that agronomic optimum may vary from one location to another. It was high at Mudende location and low at Rwerere location, the two locations showed dissimilarities associated with soil quality (Tables 3.2, 4.1- 4.3) and weather conditions (Table 3.1).The results of this study are consistent with findings of other researchers indicating that agronomic optimum nitrogen rate depends on soil quality (Boiteau *et al.*, 2014), weather conditions, genetic factors and chemical form of the fertilizer being applied (Kelling *et al.*, 2014).

Principal component analysis for aggregate potato yield

Agronomic traits such as stem height, leaf area index, number of tubers per plant, fresh tuber weight, medium and large sized tuber yield and marketable tuber yield depicted a positive impact on aggregate potato yield, and expressed high potentialities to enhance potato aggregate yield. Other agronomic parameters like small and unmarketable tuber yield showed negative impact on aggregate potato yield, therefore were described as yield limiting traits.

According to the results of principal component analysis (PCA) and with the aim to optimize potato tuber yield, it is worthy to optimize the effect of any factor which is likely to enhance variables associated with positive loadings (stem height, leaf area index, number of tubers per plant, fresh tuber weight, medium and large sized tuber yield, marketable tuber yield).Contrarily, there is a need to minimize the effect of any factor which is expected to enhance variables with negative loadings (small and unmarketable tuber yield).

Relatively more variations were evident in the traits which were located on the first principal component. The important variables considered in this PC were stem height, leaf area index, number of tubers per plant, average fresh tuber weight, medium and large sized tuber yields, and marketable tuber yield for selection towards positive direction; small and unmarketable tuber potato yield for selection towards negative direction. These above variables might be taken into consideration for effective primary macronutrients management for enhanced potato yield. PCA demonstrated that agronomic traits such as stem height, leaf area index, number of tubers per plant, average fresh tuber weight, medium and large sized tuber yields, and marketable tuber yield positively imparted most to the observed total tuber yields. The research findings are in agreement with the findings of Moinuddin and Bansal (2005); Khayatnezhad *et al.* (2011); Singh and Lal (2012), Maralian *et al.* (2014); Birtukan (2016) and Mishra *et al*. (2018). The PCA proved that agronomic attributes such as small and unmarketable tuber yields contributed most, but negatively, to the observed aggregate tuber yields. The results are in agreement with research findings highlighted by Moinuddin and Bansal (2005), Singh and Lal (2012) and Birtukan (2016).

The contribution to the variation of potato yield of the second PC, containing number of main stems per plant as unique variable, was lower compared to input of the first one, but the trait contribution was positive. The reason of this least contribution of the trait is due to that there was no significant effects of fertilizer factors (N, P and K nutrient rates) on the attribute. This could be due to the fact that the number of main stems per plant is much more influenced by the inheritance of the potato crop rather than by external (environmental) factors (Felenji *et al.*, 2011; Darabad, 2014; Yousif *et al.*, 2015). In fact, the number of main stems per plant can be influenced by varietal genetic makeup, seed tuber size, and physiological age of the seed, storage conditions, and number of viable sprouts at planting, sprout damage at the time of planting and crop management; but not by mineral fertilization (Mulubrhan, 2004; Zelalem *et al.*, 2009; Felenji *et al.*, 2011; Darabad, 2014; Yousif, 2015).

However, the factors highlighted above were not considered as variables during the present study; the only independent variables were nitrogen, phosphorus and potassium nutrient rates.

5.3 Effect of Nitrogen, Phosphorus and Potassium on potato quality attributes

The results of single site ANOVA and ANOVA on pooled basis revealed that the main effects of location, N, P, K and their interaction effects N × P × K were significant ($p < 0.05$) on potato processing and nutritional quality attributes whereas effects of season were not. In fact, the agrotechnical treatments can influence both the yield and technological value of potatoes (Thybo *et al.*, 2002). Both the yield and the chemical composition of potato tubers are, to a large extent, dependent on fertilizer rates (Bélanger *et al.*, 2002).

According to the results, increasing rate of nitrogen increased reducing sugar, crude protein and ascorbic acid content while it decreased potato specific gravity, starch, dry matter and crude ash content. Actually, potato growers are paid based on a combination of yield and tuber quality factors. Specific gravity has been used as a criterion of potato quality because of its close relationship to starch and dry matter content and finally for determining the processing quality of potato tubers (Abebe *et al.,* 2013). Increasing rate of N led to statistically significant decrease of potato specific gravity. This reduction in specific gravity might be due to the fact that N level increase was restraining starch and dry matter accumulation in tubers. The results of the present study are in agreement with findings of many researchers (Bélanger *et al.,* 2002; Zebarth *et al.,* 2004; Ahmed *et al.,* 2009; Ahmed *et al.,* 2015; Zewide *et al.,* 2016) who reported decrease of specific gravity with increased N level application. Moreover, increasing rate of N had negative effect on starch and dry matter content in potato tubers. The higher the N application rate, the lower were the starch and dry matter content. The reduction in starch and tuber dry matter content with increased N rate application could be attributed to the production of high quantity of gibberellins hormone induced by high N application which in turn limited partitioning of photoassimilates to the tuber. The results are consistent with research results of Ahmed *et al.* (2009), Ahmed *et al.* (2015) and Zewide *et al.* (2016).

The research results revealed the existence of a positive association between N fertilizer level and reducing sugar content in tubers. In fact, reducing sugar content of potato tubers is of great importance in relation to processing, especially for fried products. The chip color is dependent on the 'Maillard reaction' between reducing sugars and free amino acids.

A positive correlation of intensity of chip colour to reducing sugar content was reported by Amjad *et al.* (2017). The results of the present study revealed that reducing sugar content in tubers increased with levels of nitrogen application; they are in harmony with the findings of Sandhu *et al.* (2010). Nitrogen fertilization significantly increased crude protein content in potato tubers. The positive influence of N on crude protein content is mainly due to accumulation of N content during tuber bulking stage which led to formation of more amino acids and increase in tuber protein content. The results of the present research are in agreement with the findings of Ahmed *et al.* (2009); Yassen *et al.* (2011) and Ahmed *et al.* (2015) who testified increase of crude protein content in potato tubers with increase of N level application. A similar pattern was observed when ascorbic acid content was measured where increasing N application caused a significant increase of ascorbic acid content in potato tubers. Lakshmi (2010) also found that nitrogen application had a positive influence on vitamin C content in potato tubers.

Increasing rate of phosphorus decreased specific gravity, starch, dry matter and reducing sugar and crude ash content while it increased crude protein and ascorbic acid content in potato**.** In this line, increasing rate of Phosphorus led to statistically significant decrease of potato specific gravity, starch and dry matter content. This negative association might be due to the fact that Phosphorus level increase was not boosting starch and dry matter accumulation in potato tubers. The present results are consistent with findings of other researchers who focused their works on effects of Phosphorus fertilizer rates on potato processing and nutritional attributes. In this line, Assefa, (2005), Daniel (2006) and Zewide *et al.* (2016) indicated that increasing level of Phosphorus resulted in decrease of potato specific gravity, starch and dry matter content in potatoes while Magali *et al.,* 2017) pointed out the increase of crude protein in potatoes tubers due to progressive increase of Phosphorus levels. In addition, White *et al.* (2008) highlighted a positive effect of phosphorus level application on ascorbic acid content in potato tubers. However, an opposite pattern was observed when reducing sugar content was measured where increasing P application caused a significant decrease in reducing sugar content in potato tubers. These results are in line with findings of Magali *et al.* (2017) who underlined the existence of negative association between P fertilizer application and reducing sugar content in potato tubers.

Different researchers specified the presence of a relationship between potassium fertilizer application and potato processing and nutritional attributes. In the present study, increasing rates of Potassium increased specific gravity, starch, dry matter, crude protein and ascorbic acid content while it decreased potato reducing sugar and crude ash content. This positive association might be due to the fact that Potassium level increase was enhancing starch and dry matter accumulation in potato tubers. Actually, K plays an important role in the transport of assimilates and nutrients. The photosynthesis products (photosynthates) must be transported from the leaves (sources) to the site of their use or storage (sinks). Potassium promotes phloem transport of photosynthates (mainly sucrose and amino acids) to the physiological sinks, the tubers. The crucial importance of potassium in tuber quality formation stems from its role in promoting synthesis of photosynthates and to enhance their conversion into starch, protein and vitamins (Bansal and Trehan, 2011). In fact, Zameer Khan *et al.* (2010); Bansal and Trehan (2011); Arafa *et al.* (2012) and Haddad *et al.* (2016) reported an increase of specific gravity of potato tubers due to positive variation of Potassium fertilizer level. Moreover, Arafa *et al.* (2012) reported a progressive increase of starch and dry matter with increase of Potassium level. The results of the present research are also in agreement with the findings of Abd El-Latif *et al.* (2011) and Arafa *et al. (*2012) who proved that increase of Potassium levels led to increase of crude protein content in potato tubers. In the same line, the results of the present study revealed that ascorbic acid content in tubers increased with levels of Potassium; the positive effect of K levels application on ascorbic acid content had been also reported by Lakshmi (2010), Arafa et *al. (*2012) and Haddad *et al.* (2016). An opposite pattern was observed when reducing sugar content was measured where increasing K application caused a significant decrease in simple sugar content in potato tubers as it was also reported by Gerendás *et al.* (2007) and Bansal and Trehan (2011).

Potato crude ash content decreased with increase of N, P and K fertilizer rates. The effects of N, P and K fertilizers application increased potato yield without a proportional increase in mineral nutrient content; in fact, it resulted in a lower mineral nutrient concentration. The findings are in conformity with findings of other researchers (Davis, 2005) who indicated that yield-enhancing methods like fertilization and irrigation resulted in decreased concentrations of ash in produce because of a ‘‘dilution effect’’ caused by plant growth rates exceeding the ability of plants to acquire mineral elements. White *et al.* (2008) did a research on effects of fertilizer application on potato chemical composition; he noticed that the negative control (treatment without application of any fertilizer) had higher mineral contents and this was attributed to concentration effect due to lower metabolic activity.

Potato tubers destined for processing must meet certain requirements especially for specific gravity, starch, dry matter and reducing sugar (Mohammed, 2016). Potato tubers with

> 1.080, > 14%, > 20% and < 0.30% of specific gravity, starch, dry matter and reducing sugar content, respectively are found to be suitable for making French fries, chips and dehydrated potatoes (flakes) (Elfnesh *et al.*, 2011; Hassanpanah *et al.*, 2011). However, tubers with < 1.080, < 14% and < 20% of specific gravity, starch and dry matter content, respectively are suitable for making potato salad, whole boiled and canned potatoes (Mohammed, 2016). Dry matter content of potato tubers is an important quality criterion influencing their suitability for potato processing. A high dry matter content will improve the processing efficiency and quality of the finished product. If dry matter content is too low, French fries will be too soft. More energy and oil will also be required in processing as more water must be evaporated (Agblo and Scanlon, 2002). High dry matter content increases chip yield, crispy consistency, and reduces oil absorption during cooking. Tubers with very high dry matter content produces too hard and dry French fries and too brittle crisps (Haase *et al.*, 2007). With regard to the results of the present study, except $N_{100}P_{100}K_0$, $N_{50}P_{100}K_0$ and $N_0P_{100}K_0$ treatment combinations which were suitable for making potato salad, whole boiled and canned potatoes, all other treatment combinations were suitable for making French fries, chips and dehydrated potatoes (flakes).

Effects of location on potato processing and nutritional quality attributes were found to be significant; they can be attributed to site specific characteristics. Actually, a wide variety of factors has impact on potato processing and nutritional quality. These include genetic, environmental factors (location of potato fields, weather and soil conditions) and agricultural practices (fertilizer rates, irrigation, pesticide treatments, planting and harvesting dates) (Agblo and Scanlon, 2002; White *et al.*, 2008). The differences in chemical composition of potato tubers (the same genotype) grown in various locations result from differentiated environmental conditions, especially the weather and soil types (Agblo and Scanlon, 2002).

Conflicting results (positive, negative or neutral effect) have been reported by different researchers regarding the effect of N, P and K fertilization on potato processing and nutritional attributes (Zelalem *et al.*, 2009; Kingori *et al.*, 2015; Belachew, 2016 and Girma *et al.*, 2017). The differences in response of potato processing and nutritional attributes to N, P and K fertilization stem from differentiated environmental conditions, especially the soil and weather types (Agblo and Scanlon, 2002). The differences in the quality of the same potato cultivar are likely due to different and significant genotype × environment interaction effects or responses of the metabolic process in the plant to different environmental conditions under which the crop is grown. Taking into account a wide range of factors determining potato processing and nutritional attributes (cultivar, availability of nutrients in the soil, fertilization process, plant maturity and climate), it may happen that the same cultivar, grown in one region can be suitable for manufacturing of a range of products and unacceptable when grown elsewhere, due to the variation in the processing features and chemical composition (Abubaker *et al.,* 2011; Ekin, 2011; Elfnesh *et al.*, 2011).

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

From the research results, it is concluded that there was soil fertility gradient between locations and between farms within location. Soil fertility ratings varied generally from low to medium; Mudende was comparatively more fertile than Rwerere.

N, P and K fertilizers significantly affected all potato growth (except number of stems per plant), yield and quality traits; their rates affected positively the majority of potato growth and yield parameters and the interaction N × P × K effect was significant on all potato growth (except number of stems per plant), yield and quality attributes. Combination of high N, P and K nutrient rates enhanced potato growth and yield. Location and season significantly affected all potato growth (except number of stems per plant) and yield traits. Mudende and season 2 (March-June, 2017) performed better than their pairs. The effect of location on all potato quality traits was significant while it was not at all with regard to season.

6.2 Recommendations

Based on the research results, the following recommendations are formulated:

i). To sensitize potato producer about heterogeneity in soil fertility detected between locations and between farms within location and its effects on potato yield and quality.

ii). Adoption of $N_{50}P_{100}K_{50}$ at Mudende (Birunga highlands AEZ) and $N_{100}P_{100}$ K_{50} at Rwerere (Buberuka highlands AEZ) is expected to increase potato yields up to more than three times the national average. However, adoption of fertilizer recommendations should be done according to potato end uses or market segment to supply.

iii). To order for blended NPK fertilizers with formulation responding to 1:2:1 and 2:2:1 ratio for potato growers in Birunga highlands AEZ and Buberuka highlands AEZ, respectively.

iv). Grow potato at Mudende site (Birunga highlands AEZ) preferably for direct and fresh potato consumption and at Rwerere site (Buberuka highlands AEZ) for potato processing destination. In both cases, season 2 (March-June) is more efficient.

v). To conduct further studies, using a wide range of P and K rates to determine optimal agronomic N, P and K nutrient combination rates for enhanced potato at both locations. There is also a need to conduct an economic analysis on potato fertilization in order to identify site-specific and economic optimum combination on N, P and K nutrient rates**.**

REFERENCES

Abalo, G., Hakiza, J. J., Kakuhenzire, R. M., EL-Bedewy, R. and Adipala, E. (2001). A growing performance of twelve elite potato genotypes in southwestern Uganda. *African Crop Science Journal*, 9, 17–23.

Abd El-Latif, K. M., Osman, E. A., Abdullah, R. and Kader, A. (2011). Response of potato plants to potassium fertilizer rates and soil moisture deficit. *Advances in Applied Science Research*, 2(2), 388–397.

Abebe, T., Wiersum, K. F. and Bongers, F. (2010). Spatial and temporal variation in crop diversity in agroforestry homegardens of southern Ethiopia. *Agroforestry Systems*, 78, 309–322.

Abebe, T., Wongchaochant, S. and Taychasinpitak, T. (2013). Evaluation of speci fic gravity of potato varieties in Ethiopia as a criterion for determining processingquality. *Journal of Natural Sciene*,41, 30–41.

Abubaker, S., Abu Rayyan, A., Amre, A., Alzubi1, Y. and Hadidi, N. (2011). Impact of cultivar and growing season on potato (*Solanum tuberosum* L.) under center pivot irrigation system. *World Journal of Agricultural Sciences*, 7(6), 718–721.

Adhanom, D. and Toshome, T. (2016). Characterization and classification of soils of Aba-Midan sub-watershed in Bambasi Wereda, West Ethiopia. *International Journal of Scientific and Research Publications*, 6(6), 390–399.

Adhikary, B. H. andKarki, K. B. (2006). Effect of potassium on potato tuber production in acid soils of Malepatan, Pokhara. *Nepal Agriculture Research Journal*,7, 42–48.

Agblor, A. and Scanlon, G. (2002). Effect of storage period , cultivar and two growing locations on the processing quality of French fried potatoes, *American Journal of Potato Research*,79, 167–172.

African Potato Association (APC). (201). In Rwanda, Kinigi is still the leading potato variety on the market. Kigali, Rwanda: APA.

Ahmed, A. A., Zaki, M. F., Shafeek, M. R., Helmy, Y. I. and Abd El-baky, M. M. H. (2015). Integrated use of farmyard manure and inorganic nitrogen fertilizer on growth , yield and quality of potato (*Solanum tuberosum* L.*). International Journal of Current Microbiology and Applied Sciences*,4(10), 325–349.

Ahmed, A., Abd El-baky, M., Ghoname, A., Riad, G. and El-Abd, S. (2009). Potato tuber quality as affected by nitrogen form and rate. *Middle Eastern and Russian Journal of Plant Science and Biotechnology*, 3(1), 47–52.

Al-Kaisi, M. and Kwaw-Mensah, D. (2017). *Iowa soil health field guide*. Iowa State, USA: Iowa state University.

Alemayehu, T. G., Nigussie, D. andTamado, T. (2015). Response of potato (*Solanum tuberosum*, L.) Yield and yield components to nitrogen fertilizer and planting density at Haramaya, Eastern Ethiopia. *Journal of Plant Sciences*, 3, 320–328.

Allison, M. F., Fowler, J. H. and Allen, E. J. (2001). Effects of soil and foliar-applied phosphorus fertilizers on the potato (*Solanum tuberosum*L) crop. *Journal of Agricultural Sciences*, 137, 379–395.

Amjad, A., Randhawa, M. A., Butt, M. S., Asghar, M., Yada, R. Y.and Pinhero, R. (2017). Screening potato cultivars for low sugar accumulation during storage at various storage temperatures.*Pakistan Journal of Agriculture and Science*, 54(2), 343–347.

Andersson, S., Nilsson, S. I. and Saetre, P. (2000). Leaching of dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) in humus as affected by temperature and pH. *Soil Biology and Chemistry*, 32, 1–10.

AOAC. (2000). *Official Method of Analysis association of official chemists.17th ed.* Maryland, USA: Association of Official Analytical chemists (AOAC).

AOAC. (2005). *Official methods of analysis 18et ed*. Washington, DC, USA: Association of Official Analytical chemists (AOAC).

Arafa, A. A., Hussien, S. F. M. and Hager, S. G. M. (2012). Response of tuber yield quantity aand quality of Potato plants and its economic consideration to certain bioregulators or effective microorganisms under potassium fertilization. *Journal of Plant Production*, 3(1), 131–150.

Askegaard, M., Eriksen, J. and Johnston, A. E. (2004). Sustainable management of potassium. In P. Schjonning, S. Elmholt and C. B.T. (Eds.), *Managing soil quality: Challenge in modern agriculture* (pp. 85–102). London, U.K.: CAB International.

Assefa, N. (2005). *Response of two improved potato varieties to Nitrogen and Phosphorus application*. MSc Thesis, Alemaya University.

Ayele, T., Tanto, T. and Ayana, M. (2013). Rating and correlating physicochemical properties of Eutric vertisols in Abaya Chamo lake basin, South-West Ethiopia. *Internaational Journal of Agronomy and Plant Production*,4, 559–568.

Babu, M. V. S., Reddy, M. C., Subramanyam, A. and Balaguravaih, D. (2007). Effect of integrated use of organic and inorganic fertilizers on soil properties and yield of sugarcane. *Journal of the Indian Society of Soil Science*, 55(2), 161–166.

Baligari, V. C., Fageria, N. K. and He, Z. L. (2001). Nutrient use efficiency in plants. *Communication in Soil Science and Plant*, 32(7-8), 921-950.

Bansal, S. K. and Trehan, S. P. (2011). Effect of potassium on yield and processing quality attributes of potato. *Journal of Agricultural Science,* 24(1), 48–54.

Barker, A. V. and Pilbeam, D. J. (2006). *Handbook of Plant Nutrition*. Boca Raton, FL, USA: CRC Press.

Barto, E. K. and Cipollini, D. (2009). Testing the optimal defence theory and the growth-differentiation balance hypothesis in Arabidopsis thaliana. *Oecologia*, 146, 169–178.

Bassirani, N., Abolhassani, M. and Galavi, M. (2011). Distribution of available micronutrients as related to the soil characteristics of Hissar, Haryana (India). *African Journal of Agricultural Resesearch,* 6, 239–242.

Basumatari, A., Das, K. N. and Borkotoki, B. (2010). Interrelationships of sulphur with soil properties and its availability index in some rapeseed growing inceptisols of Assam. *Journal of the Indian Society of Soil Science,* 58(4), 394–402.

Bationo, A., Waswa, B., Kihara, J. and Kimetu, J. (2007). *Advances in Integrated Soil Fertility Management in sub-Saharan Africa: Challenges and Opportunities*. The Netherlands: Springer City.

Bationo, A. (2004). *Managing nutrient cycles to sustain soil fertility in Sub- Saharan Africa*. Nairobi, Kenya: Academy Science Publishers (ASP) in association with the Tropical soil biology and fertility institute of CIAT.

Bekalo, T. G. (2017). *Potato productivity, nutrient use efficiency and soil chemical property as influenced by organic and inorganic amendments in arbegona district, Southern Ethiopia*. Msc Thesis, Hawassa University, Ethiopia.

Belachew, B. (2016). *Effect of Nitrogen and Phosphorus rates on growth, yield, yield components and quality of potato (Solanum tuberosum*,L.*) at Dedo, South West Ethiopia*. MSc Thesis, Jimma University.

Bélanger, G., Walsh, J. R., Richards, J. E., Milburn, P. H. and Ziadi, N. (2000). Comparison of three statistical models describing potato yield response to nitrogen fertilizer. *Agronomy Journal*, 92, 902–908.

Bélanger, G., Walsh, J. R., Richards, J. E., Milburn, R. H. and Ziadi, N. L. (2002). Nitrogen fertilization and irrigation affects tuber characteristics o f two potato cultivars. *Canadian Journal of Soil Science,* 79, 269–279.

Bell, R. W. and Dell, B. (2008). *Micronutrients for Sustainable Food, Feed, Fibre and*

Bioenergy Production (1st ed.). Paris, France: IFA.

Bezabih, B., Aticho, A., Mossisa, T. and Dume, B. (2016). The effect of land management practices on soil physical and chemical properties in Gojeb sub-river basin of Dedo District , Southwest Ethiopia. *Journal of Soil Science and Environmental Management*, 7, 154–165. Available at https://doi.org/10.5897/JSSEM2016.0574. [Accessed 2 April 2017]

Birasa, E., Bizimana, I., Bouckaert, W., Deflandre, A., Chapelle, J., Gallez, A.,Vercruysse, J. (1990). *Carte Pédologique du Rwanda*. Kigali, Rwanda: MINAGRI.

Birtukan, B. (2016). *Effect of nitrogen and phosphorus rates on growth, yield, yield components and quality of potato (Solanum tuberosum L.) at Dedo, South West Ethiopia*. MSc thesis, Jimma University, Ethiopia.

Bizoza, R. A. and Byishimo, P. (2013). Agricultural Productivity and Policy Interventions in Nyamagabe District, Southern Province Rwanda, *Rwanda Journal*, 1 (1): 3-19.

Boiteau, G., Goyer, C., Rees, H. W. and Zebarth, B. J. (2014). Differentiation of potato ecosystems on the basis of relationships among physical, chemical and biological soil parameters. *Canadian Journal of Soil Science*, 94, 463–476.

Boyd, N.S., Gordon, R. and Martin, R. C. (2002). Relationship between leaf area index and ground cover in potato under different management conditions. *Potato Research*,45(1), 117–129.

Brady, N.C. and Weil, R. R. T. (2002). *The nature and properties of soils* (13th ed.). New Jersey: Pearson Education.

Brady, N.C. and Weil, R. R. T. (2008). *The nature and properties of soils*. New Jersey: Prentice Pearson-Hall, Upper Saddle River.

Bruce, R. C. and Rayment, G. E. (1982). *Analytical methods and interpretations used by the Agricultural Chemistry Branch for Soil and Land Use Surveys*. Indooroopilly, Queensland,Australia: Brisbane, Queensland. Dept. of Primary Industrie.

Bruulselma, T. W., Fixen, P. E. and Sulewski, G. D. (2012). *4R Plant Nutrition Manual: A Manual for Improving the Management of Plant Nutrition*. Norcross, GA, USA.: International Plant Nutrition Institute (IPNI).

Bucagu, C., Mbonigaba, J. J. M. and Uwumukiza, B. (2013). Effects of mineral and organic fertilizers on crop productivity and nutrient use efficiency in smallholder farms of Southern Rwanda. *Rwanda Journal*, 1, 15–34.

Burera District. (2013). *District development plan (2013-2018)*. Kigali, Rwanda: MINALOC.

Burga, S., Dechassa, N. andTsegaw, T. (2014). Influence of mineral nitrogen and potassium fertilizers on wand seed potato production on alluvial soil in Eastern Ethiopia. *East African Journal of Sciences*, 8(2), 155–164.

Carter, M. R. (2002). Soil quality for sustainable land management: Organic matter and aggregation interactions that maintain soil functions. *Agronomy Journal,* 94, 38–47.

Cui, Z., Chen, X., Ju, X. and Zhang, F. (2014). Mnaging agricultural nutrients for food security in China: past, present and futuire. *Agronomy Journal,* 106, 191-198.

Dampney, P., Johnson, P., Goodlass, G., Dyer, C., Sinclair, A. and Edwards, T. (2002). *Review of the Response of Potatoes to phosphate.* London, U.K.: Department for Environment, Food and Rural Affairs.

Daniel, Z. Z, Sewa, L., Tesfai, T. K. and Biniam, M. G. (2016). Effect of Potassium levels on growth and productivity of potato Varieties. *American Journal of Plant Sciences*,7(1), 1629–1638.

Daniel, M. (2006). *Effect of integrated nutrient management on agronomic performance of potato (Solanum tuberosum,* L*) and fertility on nitosol at Bako.* MSc Thesis, Alemaya University.

Darabad, G. (2014). Study the relationships between yield and yield components of potato varieties using correlation analysis and regression analysis and causality. *International Journal of plant, Animal and Environmental Sciences*, 4(2), 584–589.

Darwish, T. M., Atallah, T. W., Hajhasan, S. and Haidar, A. (2006). Nitrogen and water use efficiency of fertigated processing potato. *Agricultural water management*,85(1–2), 95–104. Available at https://doi.org/10.1016/j.agwat.2006.03.012.[Accessed 14 March 2017]

Das, S. K., Banerjee, H., Chakraborty, A. and Sarkar, A. (2015). Production potential of newly released potato (*Solanum tuberosum*, L.) cultivars under different nitrogen levels, 13(2), 121–130.

Davis, D. R. (2005). Trade-Offs in Agriculture and Nutrition. *Food technology*, 59(3), 120.

De la Rosa, D. (2005). Soil quality evaluation and monitoring based on land evaluation. *Land Degradation and development*, 16, 551–559.

De la Rosa, D., Mayol, F., Diaz-Pereira, E., Fernandez, M. and De la Rosa, D. J. (2004). A land evaluation decision support system (MicroLEIS DSS) for agricultural soil protection. *Environmental Modelling and Software*, 19, 929–942.

Debashis, M. (2015). *Performance of potato cv. Kufri Ashoka as influenced by graded levels* *of N, P and K*. MSc Thesis, Orissa University of Agriculture and Technology, India.

Dechassa, N. and Schenk, M. K. (2004). Exudation of organic anions by roots of cabbage, carrot and potato as influenced by environmental factors and plant age. *Journal of Plant Nutrition and Soil Sciences*, 167, 623–629.

Dibbs, D. (2000). The mysteries (myths) of nutrient use efficiency. *Better crops*, 84, 3–4.

Dinesh, K., Ezekiel, R., Singh, B. and Ahmed, I. (2005). Conversion table for specific gravity dry matter and starch content from under water weight of potatoes grown in North India plains. *Potato Journal*, 32, 79–84.

Donohue, K., Dorn, L., Griffith, C., Kim, E., Aguilera, A., Polisetty, C. R. and Schmitt, J. (2009). Environmental and genetic influences on the germination of arabidopsis thaliana in the field. *Evolution Volume*, 59, 740–757.

Drechsel, P., Heffer, P., Magen, H., Mikkelsen, R., Singh, H. and Wichelns, D. (2015). Managing water and nutrients to ensure global food security, while sustaining ecosystem services. In *Managing water and fertilizer for sustainable Agricultural intensification* (pp. 1–8). IFA, IWMI, IPNI and IPI.

Duong, T. T. T. (2013). *Compost effects on soil properties and plant growth*. PhD Thesis, University of Adelaide.

Ekin, Z. (2011). Some analytical quality characteristics for evaluating the utilization and consumption of potato (Solanum tuberosum L.) tubers. *African Journal Of Biotechnology*, 10(32), 6001–6010.

Elfnesh, F., Tekalign, T. and Solomon, W. (2011). Processing quality of improved potato (*Solanum tuberosum*, L.) cultivars as influenced by growing environment and blanching, *5*(6), 324–332.

Ewing, E. E. and Struik, P. C. (1992). Tuber formation in potato: induction, initiation, and growth. *Horticultural reviews*, *14*, 89–197.

FAO–FDCO. (2004). *Integrated nutrient management-A glossary of terms*. Rome, Italy: Food and Agriculture Organization of the United Nations.

FAO. (2015). *Boosting African's soils-From the Abuja declarations on fertilizers to a sustainable soil management framework for food and nutritional security in Africa by 2030*. Rome, Italy: FAO.

Felenji, H., Aharizad, S., Afsharmanesh, G. and Ahmadizadeh, M. (2011). Evaluating correlation and factor analysis of morphological traits in potato cultivars in fall cultivation of Jiroft area. *American-Eurasian Journal of Agricultural and*

*Environemental Sciences,*11(5), 679–684.

Feltran, J. C, Lemos, L. B and Vieites, R. L. (2004). Technological quality and utilization of potato tubers, *Journal of Agricultural Science,*61(6): 598–603.

Fernandes, A. M. and Soratto, R. P. (2012). Nutrition, dry matter accumulation and partitioning and phosphorus use efficiency of potato grown at different phosphorus levels in nutrient solution. *Revista Brasileira de Ciencia do Solo,* 36, 1528–1537.

Fontes, P. C. R., Braun, H., Busato, C. and Cecon, P. R. (2010). Economic optimum nitrogen fertilization rates and nitrogen fertilization rate effects on tuber characteristics of potato cultivars. *Potato Research*, *53*(3), 167–179.

Franke, A.C., Baijukya, F., Kantengwa, S., Reckling, M., Vanlauwe, B. and Giller, K. E. (2016). Poor farmers – poor yields: socio-economic, soil fertility and crop management indicators affecting climbing bean productivity in northern Rwanda. *Experimental Agricultural*, *4*, 1–21.

Gayler, S., Wang, E., Riesack, E., Schaaf, T. and Maidl, F. (2002). Modeling biomass growth, N-uptake and phenological development of potato crop. *Geoderma*, *105*(3–4), 367–383.

Geremew, E. B., Steyn, J. M. and Annandale, J. G. (2007). Evaluation of growth performance and dry matter partitioning of four processing potato (*Solanum tuberosum,*L.) cultivars. *New Zealand Journal of Crop and Horticultural science*, 35(3), 385–393.

Gerendás, J., Heuser, F. and Sattelmacher, B. (2007). Influence of nitrogen and potassium supply on contents of acrylamide precursors in potato tubers and on acrylamide accumulation in French fries. *Journal of Plant Nutrition,*30, 1499–1516.

Ghulam, A. (2011). *Evaluation and selection of potato genotypes for better yield, storage and processing attributes.* PhD Thesis, Arid Agriculture University Rawalpindi, Pakistan.

Gilbert, N. (2009). Environment: the disappearing nutrient. *Nature*, 461, 716–718.

Girma, C., Abebe, C. and Zeleke, O. (2017). Response of Applied Phosphorus Fertilizer Rate and Plant Spacing for Potato (*Solanum tuberosum*, L.) production on nitisols in central highland of Ethiopia. *Greener Journal of Agricultural Sciences*, 7(9), 255–262.

Grant, C. A., Flaten, D. N., Tomasiewicz, D. J. and Sheppard, S. C. (2001). The importance of early season phosphorus nutrition. *Canadian Journal of Plant Science*, 81, 211–224.

Gregory, D. I. and Bumb B. L. (2006). *Factors Affecting Supply of Fertilizer in Sub-Saharan*

Africa The World Bank, Washington, DC. Washington, DC: The World bank.

Grossman, R. B., Harms, D. S., Seybold, C. A. and Herrick, J. E. (2001). Coupling use-dependent and use-invariant data for soil quality evaluation in the United States. *Journal of Soil and Water Conservation*, 56, 63–68.

Guler, S. (2009). Effect of nitrogen on yield and chlorophyll of potato (*Solanum tubersum,* L .) cultivars. *Bangladesh Journal of Botany*, *38*, 163–169.

Haase, T., Schüler, C., Haase, N. U. and Heß, J. (2007). Suitability of organic potatoes for industrial processing: Effect of agronomical measures on selected quality parameters at harvest and after storage. *Potato Research*, 50(2), 115–141.

Haase, T., Schüler, C., Piepho, H.-P., Thön, H. and Heß, J. (2007). The Effect of preceding crop and pre - sprouting on crop growth, N use and tuber yield of main crop potatoes for processing under conditions of N stress. J*ournal of Agronomy and Crop Science*, 193, 270–291.

Habtam, S. (2012). *Response of potato (Solanum tuberosum,*L.*) to the application of phosphorus and potassium fertilizers at Assosa*, *Benishangul gumuz regional state, Western Ethiopia*. MSc Thesis, Haramaya University, Ethiopia.

Haddad, A. M., Al-tabbal, J. and Al-fraihat, A. (2016). Effect of different potassium nitrate levels on yield and quality of potato tubers. *Journal of Food, Agriculture and Environment*, 14(1), 101–107.

Haileslassie, A., Priess, J. A., Veldkamp, E. and Lesschen, J. P. (2007). Nutrient flows and balances at the field and farm scale: exploring effects of land-use strategies and access to resources. *Agricultural Systems*, 94, 459-470.

Hailu, A. H., Kibret, K. and Gebrekidan, H. (2015). Characterization and classification of soils of Kabe Sub-watershed in South Wollo Zone, North Eastern Ethiopia. *African Journal of Soil Science*, 3(7), 134–146.

Hassanabadi, H. and Hassanpanah, D. (2003). *Ireland breeding technical course report*. Karaj, Iran: Seed and plant improvement institute.

Hassanpanah, D., Hassanabadi, H. and Azizi Chakherchaman, S. H. (2011). Evaluation of cooking quality characteristics of advanced clones and potato cultivars. *American Journal of Food Technology*, 6(1), 72–79.

Haverkort, A. J., Uenk, D., Veroud, A. and Hand Van de Vaart, M. (2007). Relationship between ground cover, infrared reflectance of potato crops. *Potato Abstract*, 34, 119–131.

Heckman, J. R. (2007). Sweet corn nutrition uptake and removal. *HortTechnology*, 17(1), 82-86.

Herencia, J. F., García-Galavís, P. A. and Maqueda, C. (2011). Long-term effect of organic and mineral fertilization on soil physical properties under greenhouse and outdoor management Practices. *Pedosphere*, 21(4), 443–453.

Hubbard, R. K., Bosch, D. D., Marshall, L. K., Strickland, T. C., Rowland, D., Grifän, T. S. and Powell, J. M. (2008). Nitrogen mineralization from broiler litter applied to South Eastern coastal plain soils. *Journal of Soil and Water Conservation*, 63, 182–192.

IFA. (2009). *The Global "4R" Nutrient Stewardship Framework for Developing and Delivering Fertilizer Best Management Practices*. Paris, France: International Fertilizer Industry Association (IFA).

IFA, WFAO and GACSA. (2016). *Nutrient management handbook*. Paris, France: IFA and WFAO.

IFDC. (2009). *An action for developing agricultural inputs markets in Rwanda*. Kigali, Rwanda: IFDC.

IPNI. (2012). *4R Plant nutrition manual: A manual for improving the management of plant nutrition, metric version*. Norcross, USA: International Plant Nutrition Institute (IPNI).

Jamaati-E-Somarin, S., Zabihi-E-Mahmoodabad, R. and Yari, A. (2010). Response of agronomical, physiological, apparent recovery nitrogen use efficiency and yield of potato tuber (*Solanum tuberosum* L.) to nitrogen and plant density. *American-Eurasian Journal of Agricultural and Environmental Sciences*, 9(1), 16–21.

Jenkins, P.D. and Mahmood, S. (2003). Dry matter productionand partitioning in potato plants subjected to combined deficiencies of nitrogen, phosphorus and potassium. *Annals of Applied Biology*, 143(2), 215–229.

Jenkins, P. D. and Ali, H. (2000). Phosphorus supply and progeny tuber numbers in potato crops. *Annals of Applied Biology*, 136, 41–46.

Jeuffroy, M. H., Ney, B. and Qurry, A. (2002). Integrated physiological and agronomic modelling of N capture and use within the plant. *Journal of Experimental Botany*, *53,* 809–823.

Jiang, Y., Zhang, Y.G., Zhou, D., Qin, Y. and Liang, W. J. (2009). Profile distribution of micronutrients in aquic brown soil as affected by land use. *Plant Soil Environment,* 55, 468–476.

Johnston, A. E. and Milford, G. F. J. (2009). *Nitrogen and potassium interactions in crops*. York, U.K.: The Potash Development Association.

Kelling, K. A., Arriaga, F. J., Lowery, B., Jordan, M. O. and Speth, P. E. (2014). Use of hill shape with various nitrogen timing splits to improve fertilizer use efficiency. *American Journal of Potato Research,* 92, 71–78.

Khan, M. S., Shil, N. C. and Noor, S. (2008). TitIntegrated nutrient management for sustainable yield of major vegetable crops in Bangladesh. *Bangladesh Journal of Agriculture and Environment*, 4, 81–94.

Khayatnezhad, M., Shahriari, R. and Gholamin, R. (2011). Correlation and Path Analysis Between Yield and Yield Components in Potato (*Solanum tubersum,* L.). *Middle East Journal of Scientific Research*,7(1), 17–21.

Kingori, G. G., Nyamori, A. J. and Khasungu, I. D. (2015). Optimization of Seed Potato Specific density, starch and dry matter contents and tuberization capacity of resultant plants through integrated irrigation,nitrogen and phosphorus management. *Journal of Plant Sciences*, 3(4), 225–233.

Korves, T. M., Schmid, K. J., Caicedo, A. L., Mays, C., Stinchcombe, J. R, Purugganan, M. D. and Schmitt, J. (2007). Fitness effects associated with the major flowering time gene FRIGIDA in Arabidopsis thaliana in the field. *American Naturalist*, 169, 141–157.

Kumar, A., Mishra, V. N., Srivastav, L. K. and Banwasi, R. (2014). Evaluations of soil fertility status of available major nutrients (N, P and K) and micronutrients (Fe, Mn, Cu and Zn) in vertisol of Kabeerdham district of Chhattisgarh, India. *International Journal of Interdisciplinary and Multidisciplinary Studies*, 1(10), 72–79.

Kumar, A. and Yadav, D. S. (2001). Long-term effects of fertilizers on the soil fertility and productivity of a rice-wheat system. *Journal of Agronomy and Crop Science*, 186, 47–54.

Kumar, M., Trehan, S., Jatav, M. and Lal, S. (2009). Efficacy of potato (*Solanum tuberosum*, L.) cultivars under varying levels of nitrogen and growth duration in Eastern Indo-Gangetic plains. *Indian Journal of Agronomy*, 54, 63–68.

Kumar, P., Pandey, S. K., Singh, B. P., Singh, S. V. amd Kumar, D. (2007). Effect of nitrogen rate on growth, yield, economics and crisps quality of Indian potato processing cultivars. *Potato Research,* 50(2), 143–155.

Kumar, V., Malik, A., Sharma, S. and Rai, D. . (2017). Effect of nitrogen and potassium on the growth, yield and quality of potato crop (*Solanum tuberosum,* L.). *International Journal of Scientific and Engineering Research*, 8, 68–76.

Kumari, S. (2012). Influence of drip irrigation and mulch on leaf area maximization, water use efficiency and yield of potato (Solanum tuberosum L.). *Journal of Agricultural Science*, 4(1), 71–80.

Kushwah, V. S., Singh, S. P.and Lal, S. S. (2005). Effect of manures and fertilizers on potato (Solanum tuberosum L.) production. *Potato Journal*, 32, 157–158.

Laboski, C. A. M. and Kelling, K. (2007). Influence of fertilizer management and soil fertility on tuber specific gravity: a review. *American Journal of Potato Research*, 84, 283–290.

Laekemariam, F. (2015). *Soil spatial variability analysis, fertility mapping and soil plant nutrient relations in Wolaita zone, Southern Ethiopia*. PhD Thesis; Haramaya University, Ethiopia.

Laekemariam, F. (2016). Soil nutrient status of smallholder cassava farms in Southern Ethiopia. *Biological Agriculture and Horticulture,* 6(19), 12–18.

Lakshmi, D. V. (2010). *Effect of levels of Nitrogen , Potassium and their interactions on yield and quality of potato (Solanum tuberosum L.)*. MSc Thesis, Acharya N.G. Ranga Agricultural University.

Lal, R. (2009). Soils and food sufficiency. A review. *Agronomy for Sustainable Development,* 29, 113–133.

Landon, J. R. (1991). *Booker Tropical Soil Manual: a handbook for soil survey and agricultural land evaluation in the tropics and subtropics*. New York: John Wiley and Sons Inc.

Lea, P. J., Sodek, L., Parry, M. A. . J., Shewry, P. R. and Halford, N. G. (2007). Asparagine in plants. *Annerican Applied Biology*, *150*, 1–26.

Lecocur, J. and Ney, B. (2008). Chang with in potential radiation - use efficiency in field bean. *European Journal of Agronomy*, 37, 82–89.

Levy, D. and Veilleux, R. . (2007). Adaptation of potato to high temperatures and salinity-A review. *American Journal of Potato Research*, 84, 487–506.

Li, X. -Q., Scanlon, M. G., Liu, Q. and Coleman, W. K. (2006). Processing and value addition. In: J. Gopal, S. M. P. Khurana (Eds.)*, Handbook of Potato Production, Improvement, and Postharvest Management* (pp. 523–555). New York: Food Products Press.

Lin, S., Sattelmacher, B., Kutzmutz, E., Muhling, K. H. and Dittert, K. (2004). Influence of Nitrogen nutrition on tuber quality of potato with special reference to the pathway of nitrate transport into tubers. *Journal of Plant Nutrition*, 27, 341–350.

Lindsay, W. L. and Norvell, W. A. (1978). development of DTPA soil test for Zn, Fe, Mn and Cu. *Soil Science Society of American Journal*, 42, 421- 428.

Liu, C. W., Lin, K. H. and Kuo, Y. M. (2003). Application of factor analysis in the assessment of groundwater quality in a blackfoot disease area in Taiwan. *Science of the Total Environment*, 313(1–3), 77–89.

Magali, L., Ezequiel, L. do C. and Adalton, F. M. (2017). Chemical composition of potato tubers : the effect of cultivars and growth conditions. *Journal of Food Science and Technology*, *54*(8), 2372–2378.

Maiangwa, M. G., Ogunbile, A. O., Olukosi, J. and Atala, T. K. (2007). Land Degradation: theory and evidence from the north-west of Nigeria. *Journal of Application Sciences*, 39, 69–76.

Maralian, H., Nasrollahzadeh, S., Raiyi, Y. and Hassanpanah, D. (2014). Responses of potato genotypes to limited irrigation. *International Journal of Agronomy and Agricultural Research*, 5(5), 13–19.

Marton, L. (2001). Potassium effects on potato (*Solanum tuberosum* L.) yield. *Journal of Potato*,1(4), 89–92.

McBratney, A. B., Odeh, I. O., Bishop, T. F., Dunbar, M. S. and Shatar, T. M. (2000). An overview of pedometric techniques for use in soil survey. *Geoderma*, 97, 293–327.

Medhe, S. R., Takankhar, V. G. and Salve, A. N. (2012). Correlation of chemical properties, secondary nutrients and micronutrient anions from the soils of Chakur Tahisil of Latur district, Maharashtra. *An International Peer Reviewed Journal*, 1, 34–40.

Mehlich, A. (1984). Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Communication inSoil Science and Plant Analysis*, 15, 1409–1416.

Milla, R., Escudero, A. and Iriondo, J. M. (2009). Inherited variability in multiple traits determines fitness in populations of an annual legume from contrasting latitudinal origins. *Annals of Botany,* 103, 1279–1289.

MINAGRI. (2004). *Strategic Plan for Agriculture Transformation in Rwanda*. Kigali, Rwanda: Republic of Rwanda.

MINAGRI. (2011). *Strategies for sustainable crop intensification in Rwanda-Shifting focus from producing enough to producing surplus*. Kigali, Rwanda: Republic of Rwanda.

MINAGRI. (2012). *The business case for investing in the import and distribution of fertilizer in Rwanda.* Kigali, Rwanda: Republic of Rwanda.

MINAGRI. (2013). Crop assessment. Kigali, Rwanda:MINAGRI.

Minai, J. O. (2015). *Assessing the spatial variability of soils in Uganda.* MSc Thesis, Purdue University, India.

MINECOFIN. (2012). *Rwanda vision 2020 revised*. Kigali, Rwanda: Republic of Rwanda.

MINIRENA. (2004). *National Land Policy*. Kigali, Rwanda: Republic of Rwanda.

Mishra, S., Singh, J., Kumari, V. and Sharma, P. K. (2018). Studies on association between yield attributing traits in potato (*Solanum tuberosum* L .). *Journal of Pharmacognosy and Phytochemistry,*7(1), 2719–2722.

Mitscherlich, E. A. (1909). The law of the minimum and the law of diminishing soil productivity (in German). *Agricultural Yearbooks,38,* 537–552.

Mohammed, W. (2016). Specific gravity , dry Matter content , and starch content of potato (*Solanum tuberosum,* L.) varieties cultivated in Eastern Ethiopia. *East African Journal of Sciences*, 10(2), 87–102.

Mohr, R. M. and Tomasiewicz, D. J. (2011). Effect of phosphorus fertilizer rate on irrigated Russet Burbank potato. *Communications in Soil Science and Plant Analysis, 42,* 2284–2298.

Moinuddin, K. S. andBansal, S. K. (2005). Growth , yield , and economics of potato in relation to progressive application of potassium fertilizer. *Journal of Plant Nutrition, 28*(1), 183–200. Available at https://doi.org/10.1081/PLN-200042288[Accessed 13 March 2017]

Moinuddin, K. S., Bansal, S. K. and Pasricha, N. S. (2004). Influence of graded levels of potassium fertilizer on growth, yield, and economic parameters of potato. *Journal of Plant Nutrition*, 27(2), 239–259.

Mona, E. E., Ibrahim, S. A. and Mohamed, M. F. (2012). Combined effect of NPK levels and foliar nutritional compounds on growth and yield parameters of potato plants (*Solanum tuberosum,* L.). *African Journal of Microbiology Research*, 6(24), 5100–5109.

Monteith, J. L. (2000). Agricultural meteorology: Evolution and application. *Agricultural and Forest Meteorology,*103, 5–9.

Morberg, J. P. (2000). *Soil and plant analysis Manual*, Royal Veterinary and Agricultural University. Copenhagen, Denmark: Chemistry Department.

Mosier, A. R., Syers, J. K. and Freney, J. R. (2004). *Agriculture and the nitrogen cycle. assessing the impacts of fertilizer use on food production and the environment.* London, U.K.: Island Press.

Mozumder, M., Banerjee, H., Ray, K. and Paul, T. (2014). Evaluation of potato (*Solanum tuberosum*, L.) cultivars for productivity, nitrogen requirement and eco-friendly indices under different nitrogen levels. *Indian Journal of Agronomy,* 59, 327–335.

Mugo, J. N., Masinde, P. W., Ouma, A. E. and Schulte-Geldermann, E. (2013). Critical shoot Nitrogen content for potato varieties Asante and Tigoni in Kenya. *International Journal of Education and Research*,1, 1–8.

Muhammad, N., Zahid, H., Rahmdil and Niaz, A. (2015). Effect of different doses of NPK fertilizers on the growth and tuber yield of potato. *International Journal of Life Science*,9, 3098–3105.

Muhinyuza, J. B., Shimelis,H., Melis, R., Sibiya, J., Ndambe, N. M. (2012). Participatory assessment of potato production constraints and trait preferences in potato cultivar development in Rwanda. *International Journal of Development and Sustainability*, 2, 258-380.

Mujeri, M., Haider, K., Shahana, S. and Chowdhury, T. (2012). *Improving the Effectiveness, Efficiency and Sustainability of Fertilizer Use*. New Delhi, India: Global Development Network.

Mulubrhan, H. (2004). *The effects of nitrogen, phosphorus and potassium fertilization on the yield and yield components of potato (Solanum tuberosum* L.*) grown on vertisols of Mekelle area, Ethiopia*. MSc Thesis, Haramaya University.

Mustafa, K. M., Siban, S., Tahreen, T. C. and Khondoker, T. H. (2012). *Improving the effectiveness, efficiency and sustainability of fertilizer use in South Asia*. New Delhi, India: Global Development Network.

National Institute of Statistics of Rwanda [NISR]. (2012). Administrative map of Burera District. Kigali, Rwanda: Republic of Rwanda.

National Institute of Statistics of Rwanda [NISR]. (2012). Administrative map of Rubavu District. Kigali, Rwanda: Republic of Rwanda.

Nava, G., Roque, D. and Lucia, I. (2007). Effect of the nitrogen, phosphorus and potassium fertilization on the potato tuber yield. *Horticultura Brasiliera,* 25(3), 365–370.

Nazif, W., Perveen, S. and Saleem, I. (2006). Status of micronutrients in soils of district Bhimber (Azad Jammu and Kashmir). *Agricultural and Biological Sciences*, 1, 35–40.

Nazli, F., Bushra, Iqbal, M. M., Bibi, F., Zafar-ul-Hye, Kashif, M. R. and Ahmad, M. (2018). Modeling the potassium requirements of potato crop for yield and quality optimization. *Asian Journal of Agriculture and Biology*, 6(2), 169–180.

Nebiya, J. Y. (2016). *Effect of depth and rate of phosphorus fertilizer application on yield and yield related traits of potato at Haramaya, Eastern Ethiopia*. MSc Thesis, Haramaya University.

Okalebo, J.R., Gathua, K.W. and Woomer, P. L. (2002). *Laboratory Methods of Soil and Plant Analysis: A Working Manual* (2nd ed.). Nairobi, Kenya: Moi University.

Olson, J., Berry, L. (2014). *Land degradation in Rwanda: Its extent and impact.* World Bank. Available at: https://rmportal.net/library/content/frame/land-degradation-case-studies-06-rwanda/at download/file [Accessed: 15 November 2019]

Pareek, N. (2007). Soil mineralisable sulphur and sulphur availability index. *Journal of the Indian Society of Soil Science*,l3, 289–293.

Paritosh, P., Suchhanda, M. and Goutam, K. G. (2012). Status of available sulphur in surface and sub-surface soils of red and lateritic soils of West Bengal. *International Journal of Plant, animaland Environmental Science*,2, 276–281.

Patil, A. S. P. (2011). *Site specific nutrient management (SSNM) in aerobic rice (Oryza sativa, L.) for yield maximization*. PhD Thesis, University of Agricultural Sciences GKVK, Bengaluru.

Patil, V. C. (2009). Precision nutrient manaement: A review. *Indian Journal of Agronomy*, 54(2), 113–119.

Pearson, E. S. (1938). *Mathematical Statistics and Data Analysis* (2nd ed.), Belmont, CA: Duxbury.

Pedra, F., Plaza, C., Garcia-Gil, J. C.and Polo, A. (2008). Effect of municipal waste compost and sewage sludge on proton binding behavior of humic acids from Portuguese sand and clay loam soils. *Bioresource Technology*,99, 2141–2147.

Pierce, F. J. and Larson, W. E. (1998). Developing criteria to evaluate sustainable land management. In J. M. Kimble (Ed.), *Proceedings of the Eighth International Soil Management Workshop: Utilization of Soil Survey Information for Sustainable Land Use* (pp. 7–14). Lincoln, NE: USDA Soil Conservation Service, National Soil Survey Center.

Pilbram, C. J., Hebblethwaite, P. D. and Nyongesa, T. E. (2009). Effects of plant population density of determinate and indeterminate forms of common bean to growth and development. *Journal of Agricultural Science*, 194, 138–144.

Ram, C. A. (2009). Effect of NPK on Vegetative Growth and Yield of Desiree and Kufri Sindhuri Potato. *Agricultural Research Journal*, 9(1), 67–75.

REMA. (2009). *Rwanda state of environment and outlook report*. Kigali, Rwanda:Ministry of Environment and Natural Resources

RIU (Research In Use) in Rwanda. (2010). *Potato innovation platform*. Kigali, Rwanda: MINAGRI.

Rosen, C. J. and Bierman, P. M. (2008). Potato yield and tuber set as affected by phosphorus fertilization. *American Journal of Potato Research*, *85*, 110–120.

Roy, R. N., Finck, A., Blair, G. J. and Tandon, H. L. S. (2006). *Plant nutrition for food security-A guide for integrated nutrient management*. Rome, Italy: Food and Agriculture Organization of the United Nations.

Rubavu District. (2013). *District Development Plan (2013-2018)*. Kigali, Rwanda: MINALOC.

Rukundo, P., Ndacyayisenga, T., Ntizo S., Nshimiyima, J. C. and Kirimi, S. (2019). Performance of CIP and Dutch potato varieties under Rwanda climate conditions. *African Journal of Agricultural Research*, 14(32), 1454-1462.

Rushemuka, N. P., Bock, L. and Mowo, J. G. (2014). Soil science and agricultural development in Rwanda: the state of the art. A review. *Biotechnology, Agronomy, Society and Environment*, *18*, 142–154.

Rytel, E., Lisinska, G. Tajner-Czopek, A. (2013). Toxic compound levels in potatoes are dependent on cultivation methods. *ACTA Alimentaria*, *42*, 308–317.

Saha, R., Mondal, S. and Das, J. (2001). Effect of potassium with and without sulfur containing fertilizers on growth and yield of potato (Solanum tuberosum L.). *Journal of Environment and Ecology*,19(1), 202–205.

Sakin, E. (2012). Organic carbon-organic matter and bulk density relationships in arid-semi arid soils in South East Anatolia region. *African Journal of Biotechnology*, 11, 1373–1377.

Salam, M. A., Solaiman, A. R. M., Karim, A. J. M. S. and Saleque, M. A. (2014). System productivity, nutrient use efficiency and apparent nutrient balance in rice-based cropping systems. *Archives of Agronomy and Soil Science*, 60(6), 741–764.

Sanchez, P. A. (2002). Soil Fertility and Hunger in Africa. *Science*,295, 2019–2020.

Sanchez, P. and Jama, B. (2002). Soil fertility replenishment takes off in east and southern

Africa. In B. Vanlauwe, J. Diels, N. Sanginga and Merckx R. (Eds.), *Integrated plant nutrient management in sub-Saharan Africa: From concept to practice* (pp. 23–46). Wallingford, UK: CABI.

Sandana, P. (2016). Phosphorus uptake and utilization efficiency in response to potato genotype and phosphorus availability. *European Journal of Agronomy*, 76, 95–106.

Sanderson, J. B., MacLeod, J. A., Douglas, B., Coffin, R. and Bruulsema, T. (2003). Phosphorus research on potato in PEI. *Acta Horticulturae*, 619, 409–417.

Sandhu, K. S., Chinna, G. S., Marwaha, R. S., Kumar, P. and Pandey, S. K. (2010). Effect of nitrogen fertilization on yield and chipping quality of processing varieties grown in cooler north indian plains. *Potato Journal*, 37, 143–150.

Sanginga, N. and Woomer, P. L. (Eds.). (2009). *Integrated Soil Fertility Management in Africa: Principles, Practices and Deveolpmental Process*. Nairobi, Kenya: Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture.

Santos, K. C., Kawakami, J., Genú, A., M., Passos, S. and Eschemback, V. (2018). New national potato genotypes: yield response to different doses of 4-14-8 NPK fertilizer. *Horticultura Brasileira*, 36(1), 106–111. Available at https://doi.org/10.1590/s0102-053620180118.[Accessed 17 December 2018].

Sapkota, T. B., Majumdar, K. and Jat, M. L. (2014). Precision nutrient management in conservation agriculture based wheat production of Northwest India: Profitability, nutrient use efficiency and environmental footprint. *Field Crop Research*, 233–244.

SAS. (2008). *SAS/STAT ® 9.2 User's Guide*. Cary, NC., USA: SAS Institute Inc.

Sasson, A. (2012). Food security for Africa : an urgent global challenge. *Agriculture and Food Security*, *1*(2), 1–16.

Seybold, C., Mausbach, M., Karlen, D. and Rogers, H. (1998). Quantification of soil quality. In R. Lal (Ed.), *Soil processes and the carbon cycle* (pp. 387–404). Boca Raton, FL: CRC Press.

Singh and Kaur. (2009). *Advances in potato chemistry and technology*. San Diego, USA: Academic Press.

Singh, S., Bhat, Z. A. and Rehman, H. U. (2014). Influence of organic and integrated nutrient management on physico-chemical properties of soil under basmati-wheat sequence. *The Bioscan*, 9(4), 1471–1478.

Singh, S. K. and Lal, S. S. (2012). Effect of potassium nutrition on potato yield, quality and nutrient use efficiency under varied levels of nitrogen application. *Potato Journal*, 39(2), 155–165.

Stark, J. C. and Love, S. L. (2003). *Tuber quality*. Moscow: University of Idaho Extension.

Steel, R. G. D., Torrie, J. H. and Dickey, D. A. (1997). *Principles and Procedures of Statistics a Biometrical Approach (3rd ed)* . New York, USA: Mc Graw-Hill.

Stocking, M. A. (2003). Tropical soils and food security: The next 50 years. *Science,* 302, 1356–1359.

Storey, M. (2007). The Harvested Crop. In: D. Vreugdenhil (Ed.), *Potato Biology and Biotechnology Advances and Perspective*. Oxford: Elsevier.

Struik, P. C. (2007). Responses of the potato plant to temperature. In D. Vreugdenhil, J. Bradshaw, C. Gebhardt, F. Govers, D. K. L. MacKerron, M. A. Taylor and Heather R. R., *Potato Biology and Biotechnology: Advances and Perspectives* (eds) (pp. 366–396). Amsterdam: Elsevier.

Tening, A. S., Foba-Tendo, J. N., Yakum-Ntaw, S. Y. and Tchuenteu, F. (2013). Phosphorus fixing capacity of a volcanic soil on the slope of mount Cameroon. *Agriculture and Biology Journal of North America*, 4 (3) 166–174.

Thierfelder, C. T., Mombeyarara, N., Mango, L. and Rusinamhodzi. (2013). Integration of conservation agriculture in smallholder farming systems of southern Africa: identification of key entry points. *International Journal of Agricultural Sustainability*, 21, 48–56.

Thybo, A. K., Mølgaard, J. P. and Kidmose, U. (2002). Effect of different organic growing conditions on quality of cooked potatoes. Journal of the Science of Food and Agriculture,18(7), 12–18.

Tisdale, S., Nelson, W., Beaton, J. and Havlin, J. . (2003). *Soil fertility and fertilizers* (5th Ed.). India: Prentice-Hall of India.

Tittonell, P., A. Muriuki, K. D., Shepherd, D., Mugendi, K. C., Kaizzi, J., Okeyo, L., Verchot, R. C. and Vanlauwe, B. (2010). “The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa–A typology of smallholder farms.” Author: *Agricultural Systems*, 103, 83–97.

Tittonell, P., Corbeels, M., Van Wijk, M.T., Vanlauwe, B. and Giller, K. E. (2008). Combining organic and mineral fertilizers for integrated soil Fertility management in smallholder farming systems of Kenya: Explorations using the crop-soil model FIELD. *Agronomy Journal*, 100, 1511–1526.

Tittonell, P., Vanlauwe, B., Ridder, N. and Giller, K. E. (2007). Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms: Soil fertility gradients or management intensity gradients? *Agricultural Systems*, 94, 376–390.

Tittonell, P., Vanlauwe, B., Leffelaar, P. A., Rowe, E. and Giller, K. E. (2005). Exploring diversity in soil fertility management of smallholder farms in western Kenya I. Heterogeneity at region and farm scale. *Agriculture Ecosystems and Environment*, 110, 149–165.

Trehan, S. P. (2009). Improving nutrient use efficiency by exploiting genetic diversity of potato. *Potato Journal*, 36, 121–135.

Trehan, S. P., Roy, S. K. and Sharma, R. C. (2001). Potato variety differences in nutrient deficiency symptoms and responses to NPK. *Better Crops*, 15, 18–21.

Tsegaye, G. B. (2017). *Potato Productivity, Nutrient Use Efficiency and Soil Chemical Property as Influenced by Organic and Inorganic Amendments in Arbegona District, Southern Ethiopia*. . MSc Thesis, Hawassa University, Ethiopia.

Tugel, A. J., Wills, S. A. and Herrick., J. E. (2008). *Soil Change Guide: Procedures for Soil Survey and Re-source Inventory. Version 1.1*. Lincoln, NE.: National Soil Survey Center.

Umar, S. and Moinuddin, M. (2001). The effect of sources and rates of potassium application on potato yield and economic returns. *Better Crop International*, 15, 13–15.

Vanilarasu, K. and Balakrishnamurthy, G. (2014). Influences of organic manures and amendments in soil physiochemical properties and their impact on growth, yield and nutrient uptake of banana. *The Bioscan*, 9(2), 525–529.

Vanlauwe, B., Tittonell, P. and Mukalama, J. (2006). Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya. *Nutrient Cycling in Agroecosystems*, 76, 171–182.

Vanlauwe, B. and Giller, K. E. (2006). Popular myths around soil fertility management in sub-Saharan Africa. *Agriculture, Ecosystem and Environment Journal*, 116, 34–46.

Verma, V, Setia, R. K., Sharma, P. K., Khurana, M. P. S. and Kang, S. (2007). Pedospheric distribution of micronutrient cations in soil developed on various landforms in North-East Punjab. *Journal of the Indian Society of Soil Science*, 55, 515–520.

Vos, J. and MacKerron, D. K. L. (2000). Basic concepts of the management and supply of nitrogen and water in potato production. In A. J. Haverkort and D. K. L. MacKerron

(Eds.), *Management of nitrogen and water in potato production* (pp. 15–33). Wageningen, the Netherlands: Wageningen Pers.

Watson, D. J. (1947). Comparative physiological studies in the growth of field crops. I. Variation in net assimilation rate and leaf area between species and varieties, and within and between years. *Annals of Botany*, 41–76.

Weil, R.R. and Magdoff, F. (2004). Significance of soil organic matter to soil quality and health. In F. Magdoff and R. R. Weil (Eds.), *Soil Organic Matter in Sustainable Agriculture* (pp. 1–43). Boca Raton, Florida: CRC Press.

Weiner, J. H., Griepentorg, W. and Kristensen, L. (2008). Suppression of weed by spring wheat (*Triticum aestivum*) increases with crop density and spatial uniformity. *Journal of Applied Ecology*, 38, 784–790.

Westermann, D. T. (2005). Nutritional requirements of potatoes. *American Journal of Potato Research*, 82, 301–307.

Western Potato Council. (2003). *Guide to Commercial Potato Production on the Canadian Prairies.* Manitoba, Canada: Portage La Prairie.

Westoby, M., Falster, D. S., Moles, A. T., Vesk, P. A. and Wright, I. J. (2002). Plant Ecological Strategies: Some Leading Dimensions of Variation between Species. *Annual Review of Ecology and Systematics*,33, 125–159.

White, P. J., Bradshaw, J. E., Dale, M. F. B., Ramsay, G., Hammond, J. P. and Broadley, M. R. (2008). Relationships between yield and mineral concentrations in potato tubers. *HortScience*, 44(1), 6–11.

White, P. J., Broadley, M. R., Greenwood, D. J. and Hammond, J. P. (2005). *Proceedings of the International Fertiliser Society 568. Genetic modifications to improve phosphorus acquisition by roots*. York, U.K.: IFS.

White, P. J., Wheatley, R. E., Hammond, J. P. and Zhang, K. (2007). Minerals, soils and roots. In D. Vreugdenhil (Ed.), *Potato biology and biotechnology, advances and perspectives* (pp. 739–752). Amsterdam: Elsevier.

Wibowo, C., Wijaya, K., Sumartono, G. H. and Pawelzik, E. (2014). Effect of potassium level on quality traits of Indonesian potato tubers. *Asia Pacific Journal of Sustainable Agriculture, Food and Energy*, 2, 11–16.

Wienhold, B. J., Andrews, S. S. and Karlen, D. L. (2004). Soil quality: A review of the science and experiences in the USA. *Environmental Geochemistry and Health*,26, 89–95.

World Bank. (2015). Fertilizer consumption (kilograms per hectare of arable land). Catalog sources world development indicators. Available at https://www.http://data.worldbank.org/indicator/ag.CoN.fert.zs.[Accessed 12 November 2019].

Yadav, B. K. (2011). Micronutrient status of soils under legume crops in arid region of Western Rajasthan, India. *Academic Journal of Plant Sciences,* 4(3), 94–97.

Yassen, A., Safia, M. A. andSahar, M. Z. (2011). Impact of nitrogen fertilizer and foliar spray of selenium on growth , yield and chemical constituents of potato plants. *Australian Journal of Basic and Applied Sciences*,5(11), 1296–1303.

Yihenew, G.S., Anemut, F. and Addisu, S. T. (2015). The effects of land use types , management practices and slope classes on selected soil physico-chemical properties in Zikre watershed, North-Western Ethiopia. *Environment System Research*, 4, 1–7.

Yildrim, Z. and Tokusoglu, Ö. (2005). Some analytical quality characteristics of potato (Solanum tuberosum L.) minitubers (cv. NIF) developed via in -vitro cultivation. *Journal of Environmental, Agricultural and Food Chemistry, 4*(3), 416–425.

Yousif, S. A., Zamil, Q. M., Muhi, H. Y. Al and Shammari, J. A. Al. (2015). Effect of three sand types on potato vegetative growth and yield. *International Journal of Biological, Biomolecular, Agricultural, Food and Biotechnical Engineering,* 9(3), 300–303.

Yuan, F. M. and Bland, W. L. (2005). Comparison of light -and temperature- based index models of potato (Solanum tuberosum, L.) growth and development. *American Journal of Potato Research*, 82, 345–352.

Zabihi-e-Mahmoodabad, R., Jamaati-e-Somarin, S., Khayatnezhad, M. and Gholamin, R. (2011). Correlation of tuber yield whit yield components of potato affected by nitrogen application rate in different plant density. *Advances in Environmental Biology*,5, 131–135.

Zameer Khan, M., Ehsan Akhtar, M., Naeem Safdar, M., Masud Mahmood, M., Ahmad, S.and Ahmed, N. (2010). Effect of source and level of potash on yield and quality of potato tubers. *Pakistan Journal of Botany*, 42(5), 3137–3145.

Zamil, M. F., Rahman, M. M., Rabbani, M. G. and Khatun, T. (2010). Combined effect of nitrogen and plant spacing on the growth and yield of potato with economic performance. *Bangladesh Research Publication Journal*, 3, 1062–1070.

Zebarth, B. J., Drury, C. F., Tremblay, N. and Cambouris, A. N. (2009). Opportunities for improved fertilizer nitrogen management in production of arable crops in Eastern

Canada: A review. *Canadian Journal of Soil Science*, 89, 113–132.

Zebarth, B. J., Leclerc, Y., Moreau, G. and Botha, E. (2004). Rate and timing of nitrogen fertilization of Russet Burbank potato : Yield and processing quality. *Canadian Journal of Plant Science*, 84, 855–863.

Zebarth, B. J. and Rosen, C. J. (2007). Research perspective on nitrogen BMP development for potato. *American Journal of Potato Research*, 84, 3–18.

Zelalem, A., Tekalign, T. and Nigussie, D. (2009). Response of potato (S*olanum tuberosum* L.) to different rates of nitrogen and phosphorus fertilization on vertisols at Debre Berhan, in the central highlands of Ethiopia. *African Journal of Plant Science*,3, 16–24.

Zelelew, D. Z., Lal, S., Kidane, T. T. and Biniam, M. G. (2016). Effect of potassium levels on growth and productivity of potato varieties. *American Journal of Plant Sciences*, 7, 1629–1638.

Zewide, I., Ibrahim, A. M. andTadesse, S. T. (2016). Potato (*Solanum tuberosum* L .) growth and tuber quality, soil nitrogen and phosphorus content as affected by different rates of nitrogen and phosphorus at Masha District in Southwestern Etiopia. *International Journal of Agricultural Research*, 11, 95–104.

Zewide, I., Mohammed, A. and Tulu, S. (2012). Effect of different rates of nitrogen and phosphorus on yield and yield Components of Potato (*Solanum tuberosum* L.) at Masha District, Southwestern Ethiopia. *International Journal of Soil Science*, 7, 146–156.

Zhu, F., Cai, Y. Ke, J. and Corke, H. (2010). Compositions of phenolic compounds, amino acids and reducing sugars in commercial potato varieties and their on acrylamide formation. *Journal of the Science of Food and Agriculture*, 90, 2254–2262.

Zingore, S., Murwira, H.K., Delve, R.J. and Giller, K. E. (2007). Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. *Agriculture Ecosystems & Environment*, 119, 112–126.

Zingore, S., Tittonell, P., Corbeels, M., Wijk, M. T. Van and Giller, K. E. (2011). Managing soil fertility diversity to enhance resource use efficiencies in smallholder farming systems : a case from Murewa District , Zimbabwe. *Nutrient Cycling in Agroecosystem*, 90, 87–103.

APPENDICES

Appendix 1: ANOVA table for soil pH - Mudende location (L1)

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Rep	2	0.38393889	0.19196944	5.60	0.0108
Treat	11	2.66368889	0.24215354	7.06	<.0001

Appendix 2: ANOVA table for Organic Carbon - Rwerere location (L_2)

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Rep	2	0.05748889	0.02874444	5.86	0.0091
Treat	11	3.20248889	0.29113535	59.32	<.0001

Appendix 3: ANOVA table for leaf area index (70DAE)- Mudende location (L1)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Season	1	2.3154694	2.3154694	547.41	<.0001
Rep	3	52.7785139	17.5928380	4159.19	<.0001
N	2	202.9035792	101.4517896	23984.6	<.0001
P	2	46.9270292	23.4635146	5547.10	<.0001
K	1	4.1344444	4.1344444	977.44	<.0001
Season*N	2	0.0000014	0.0000007	0.00	0.9998
Season*P	2	0.0000097	0.0000049	0.00	0.9989
Season*K	1	0.0000000	0.0000000	0.00	1.0000
N*P	4	1.6188042	0.4047010	95.68	<.0001
N*K	2	0.5885931	0.2942965	69.58	<.0001
P*K	2	0.0959847	0.0479924	11.35	<.0001
Season*N*K	2	0.0001042	0.0000521	0.01	0.9878
Season*P*K	2	0.0000375	0.0000187	0.00	0.9956
Season*N*P	4	0.0000319	0.0000080	0.00	1.0000
N*P*K	4	0.5099653	0.1274913	30.14	<.0001
Season*N*P*K	4	0.0000708	0.0000177	0.00	1.0000

Appendix 4: ANOVA table for total tuber yield (t ha-1) - Mudende location (L1)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Season	1	71.755017	71.755017	166.32	<.0001
Rep	3	51.970441	17.323480	40.15	<.0001
N	2	5725.043829	2862.521915	6635.13	<.0001
P	2	2072.001554	1036.000777	2401.38	<.0001
K	1	1031.640867	1031.640867	2391.27	<.0001
Season*N	2	0.115060	0.057530	0.13	0.8753
Season*P	2	0.057235	0.028617	0.07	0.9359
Season*K	1	0.067167	0.067167	0.16	0.6940
N*P	4	524.461242	131.115310	303.92	<.0001
N*K	2	221.752135	110.876067	257.00	<.0001
P*K	2	32.120610	16.060305	37.23	<.0001
Season*N*K	2	0.076510	0.038255	0.09	0.9152
Season*P*K	2	0.134335	0.067167	0.16	0.8560
Season*N*P	4	0.230119	0.057530	0.13	0.9698
N*P*K	4	54.615019	13.653755	31.65	<.0001
Season*N*P*K	4	0.153019	0.038255	0.09	0.9858

Appendix 5: ANOVA table for potato dry matter content (%) - Mudende location (L1)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Season	1	0.0336111	0.0336111	0.06	0.8061
Rep	3	495.6073917	165.2024639	297.70	<.0001
N	2	8.2627097	4.1313549	7.44	0.0009
P	2	106.6603931	53.3301965	96.10	<.0001
K	1	56.9521778	56.9521778	102.63	<.0001
Season*N	2	0.1193181	0.0596590	0.11	0.8982
Season*P	2	0.1825347	0.0912674	0.16	0.8486
Season*K	1	0.2516694	0.2516694	0.45	0.5021
N*P	4	2.5273861	0.6318465	1.14	0.3425
N*K	2	0.2600347	0.1300174	0.23	0.7915

P*K	2	4.2339931	2.1169965	3.81	0.0252
Season*N*K	2	0.2094097	0.1047049	0.19	0.8283
Season*P*K	2	0.0240847	0.0120424	0.02	0.9785
Season*N*P	4	0.3871111	0.0967778	0.17	0.9511
N*P*K	4	7.8681944	1.9670486	3.54	0.0094
Season*N*P*K	4	0.4022361	0.1005590	0.18	0.9477

Appendix 6: ANOVA table for leaf area index (70DAE) - Rwerere location (L2)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Season	1	0.2756250	0.2756250	6.86	0.0101
Rep	3	36.7492444	12.2497481	305.07	<.0001
N	2	197.9013722	98.9506861	2464.26	<.0001
P	2	46.2198222	23.1099111	575.53	<.0001
K	1	4.2230250	4.2230250	105.17	<.0001
Season*N	2	0.0066667	0.0033333	0.08	0.9204
Season*P	2	0.0050000	0.0025000	0.06	0.9397
Season*K	1	0.0044444	0.0044444	0.11	0.7400
N*P	4	1.5933778	0.3983444	9.92	<.0001
N*K	2	0.5181167	0.2590583	6.45	0.0023
P*K	2	0.0810667	0.0405333	1.01	0.3679
Season*N*K	2	0.0022222	0.0011111	0.03	0.9727
Season*P*K	2	0.0005556	0.0002778	0.01	0.9931
Season*N*P	4	0.0033333	0.0008333	0.02	0.9991
N*P*K	4	0.4961667	0.1240417	3.09	0.0190
Season*N*P*K	4	0.0077778	0.0019444	0.05	0.9955

Appendix 7: ANOVA table for total tuber yield (t ha-1) - Rwerere location (L2)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Season	1	57.962844	57.962844	149.59	<.0001
Rep	3	48.681831	16.227277	41.88	<.0001
N	2	5098.571217	2549.285608	6579.03	<.0001
P	2	1938.965904	969.482952	2501.98	<.0001
K	1	983.345069	983.345069	2537.75	<.0001
Season*N	2	0.006806	0.003403	0.01	0.9913
Season*P	2	0.001560	0.000780	0.00	0.9980
Season*K	1	0.002844	0.002844	0.01	0.9319
N*P	4	483.337204	120.834301	311.84	<.0001
N*K	2	202.167939	101.083969	260.87	<.0001
P*K	2	28.408876	14.204438	36.66	<.0001
Season*N*K	2	0.006806	0.003403	0.01	0.9913
Season*P*K	2	0.001560	0.000780	0.00	0.9980
Season*N*P	4	0.003715	0.000929	0.00	1.0000
N*P*K	4	53.209815	13.302454	34.33	<.0001
Season*N*P*K	4	0.003715	0.000929	0.00	1.0000

Appendix 8 : ANOVA table for potato dry matter content (%) –Rwerere location (L2)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Season	1	0.0315063	0.0315063	0.06	0.8106
Rep	3	499.0061021	166.3353674	304.82	<.0001
N	2	9.6372542	4.8186271	8.83	0.0003
P	2	113.6925042	56.8462521	104.17	<.0001
K	1	65.1652562	65.1652562	119.42	<.0001
Season*N	2	0.1588542	0.0794271	0.15	0.8647
Season*P	2	0.2238792	0.1119396	0.21	0.8149
Season*K	1	0.2409174	0.2409174	0.44	0.5079
N*P	4	1.9609542	0.4902385	0.90	0.4678
N*K	2	0.2385042	0.1192521	0.22	0.8041
P*K	2	5.2279292	2.6139646	4.79	0.0102
Season*N*K	2	0.3182264	0.1591132	0.29	0.7477
Season*P*K	2	0.0493597	0.0246799	0.05	0.9558
Season*N*P	4	0.1737042	0.0434260	0.08	0.9884
N*P*K	4	10.3701292	2.5925323	4.75	0.0015
Season*N*P*K	4	0.1083903	0.0270976	0.05	0.9953

Appendix 9: ANOVA table for fresh tuber weight (g)- Pooled basis L1&2

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Location	1	6359.66420	6359.66420	2419.78	<.0001
Season	1	163.62405	163.62405	62.26	<.0001
N	2	70786.01104	35393.00552	13466.6	<.0001
P	2	25643.03623	12821.51812	4878.43	<.0001
K	1	12868.89245	12868.89245	4896.46	<.0001
Rep	3	766.35777	255.45259	97.20	<.0001
Season*Location	1	42.21273	42.21273	16.06	<.0001
Location*N	2	255.72402	127.86201	48.65	<.0001
Location*P	2	8.25782	4.12891	1.57	0.2102
Location*K	1	5.05090	5.05090	1.92	0.1671
Season*N	2	20.50708	10.25354	3.90	0.0217
Season*P	2	6.91041	3.45520	1.31	0.2707
Season*K	1	3.41040	3.41040	1.30	0.2559
N*P	4	6526.08515	1631.52129	620.77	<.0001
N*K	2	2619.60470	1309.80235	498.36	<.0001
P*K	2	520.73823	260.36911	99.07	<.0001
N*P*K	4	861.24825	215.31206	81.92	<.0001
Season*N*P	4	1.10506	0.27627	0.11	0.9806
Season*N*K	2	0.34765	0.17383	0.07	0.9360
Season*P*K	2	0.42154	0.21077	0.08	0.9230
Season*Location*N	2	55.60924	27.80462	10.58	<.0001
Season*Location*P	2	20.35818	10.17909	3.87	0.0223
Season*Location*K	1	10.36642	10.36642	3.94	0.0483
Location*N*P	4	7.95692	1.98923	0.76	0.5544
Location*N*K	2	1.15157	0.57579	0.22	0.8034
Location*P*K	2	9.61719	4.80859	1.83	0.1630
Season*Location*N*P	4	6.66385	1.66596	0.63	0.6389
Season*Location*N*K	2	2.92403	1.46202	0.56	0.5742
Season*Location*P*K	2	0.11050	0.05525	0.02	0.9792
Location*N*P*K	4	27.42147	6.85537	2.61	0.0367
Season*N*P*K	4	0.21572	0.05393	0.02	0.9992
Season*Location*N*P*K	4	0.73423	0.18356	0.07	0.9910

Appendix 10: ANOVA table for marketable tuber yield (t /ha) - Pooled basis L1&2

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Location	1	1255.63133	1255.63133	2682.30	<.0001
Season	1	78.19793	78.19793	167.05	<.0001
N	2	12005.26006	6002.63003	12822.9	<.0001
P	2	4397.03071	2198.51535	4696.51	<.0001
K	1	2224.05593	2224.05593	4751.07	<.0001
Rep	3	45.97166	15.32389	32.74	<.0001
Season*Location	1	0.00048	0.00048	0.00	0.9746
Location*N	2	55.84923	27.92462	59.65	<.0001
Location*P	2	1.18734	0.59367	1.27	0.2835
Location*K	1	0.31933	0.31933	0.68	0.4098
Season*N	2	0.06028	0.03014	0.06	0.9377
Season*P	2	0.03041	0.01520	0.03	0.9680
Season*K	1	0.03358	0.03358	0.07	0.7891
N*P	4	1036.06193	259.01548	553.31	<.0001
N*K	2	448.13144	224.06572	478.65	<.0001
P*K	2	65.42591	32.71295	69.88	<.0001
N*P*K	4	123.08787	30.77197	65.74	<.0001
Season*N*P	4	0.11541	0.02885	0.06	0.9929
Season*N*K	2	0.03567	0.01783	0.04	0.9626
Season*P*K	2	0.06468	0.03234	0.07	0.9333
Season*Location*N	2	0.06189	0.03094	0.07	0.9361
Season*Location*P	2	0.02869	0.01435	0.03	0.9698
Season*Location*K	1	0.03668	0.03668	0.08	0.7798
Location*N*P	4	2.32280	0.58070	1.24	0.2948
Location*N*K	2	1.52159	0.76079	1.63	0.1993
Location*P*K	2	1.17176	0.58588	1.25	0.2882
Season*Location*N*P	4	0.11056	0.02764	0.06	0.9935
Season*Location*N*K	2	0.03760	0.01880	0.04	0.9606
Season*Location*P*K	2	0.06546	0.03273	0.07	0.9325
Location*N*P*K	4	1.08157	0.27039	0.58	0.6792
Season*N*P*K	4	0.07671	0.01918	0.04	0.9968
Season*Location*N*P*K	4	0.07795	0.01949	0.04	0.9967

Appendix 11: Classification levels for different soil chemical attributes

11.1 Soil pH

Soil pH								
Very strongly acidic	**Strongly acidic**	**Moderately acidic**	**Slightly acidic**	**Neutral**	**Mildly alkaline**	**Moderately alkaline**	**Strongly alkaline**	**Very strongly alkaline**
4.5-5.0	5.1-5.5	5.6-6.0	6.1-6.5	6.6-7.3	7.4-7.8	7.9-8.4	8.5-9.0	> 9.0

Source: Bruce and Rayment (1982)

11.2 Other soil properties

Chemical attribute	Very low	Low	Medium	High	Very high
OC (%)	< 2.0	2.0-4.0	4.0-10.0	> 10	
N_{Tot} (%)		0.1-0.2	0.2-0.5	0.5-1.0	> 1.0
P_{Av} (ppm)		< 5.0	5.0-15.0	> 15.0	
S_{Av} (ppm)	< 2.0	2.0-6.0	6.0-10.0	10.0-15.0	> 15.0
K_{Ex} (meq/ 100g)		< 0.2	0.2-0.6	> 0.6	
Ca_{Ex} (meq/ 100g)		< 4.0	4.0-10.0	> 10.0	
Mg_{Ex} (meq/ 100g)		< 0.5	0.5-4.0	> 4.0	
CEC (meq/ 100g)	< 5.0	5.0-15.0	15.0-25.0	25.0-40.0	> 40.0
BS (%)		< 20.0	20.0-60.0	> 60.0	
Cu (ppm)	< 0.1	0.1-0.3	0.3-0.8	0.8-3.0	> 3.0
Zn (ppm)	< 0.5	0.-1.0	1.0-3.0	3.0-5.0	> 5.0
Fe (ppm)	< 2.0	2.0-4.0	4.0-6.0	6.0-10.0	>10.0
Mn (ppm)	< 0.5	0.5-1.2	1.2-3.5	3.5-6.0	> 6.0

Source: Landon (1991)

Appendix 12: Research plates: Field trials and Lab analysis

A. Field trial preparation

B. Soil lab analysis

C. Field trial on going

D. Tuber ash content

E. Tuber protein content

Appendix 13: Scientific contribution of the current study/ Article published

Title of the paper: Potato (Solanum tuberosum L.) tuber yield and yield components as influenced by different levels of nitrogen, phosphorus and potassium in Rwanda

Journal: Agricultural Science Digest

Authors: Adrien Turamyenyirijuru[1&3], Guillaume Nyagatare [2], Robert Morwani Gesimba [3] and Rhoda Jerop Birech[3]

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Abstract

Despite potato yield potential, its intensification level remain low in Rwanda, translating into low yield occasioned mainly by the decline in soil fertility. Field experiments were conducted in Birunga, Mudende [L_1]) and Buberuka, Rwerere [L_2] highlands Agro-Ecological Zones (AEZs), during September- December 2016 and March-June 2017 crop growing seasons to determine the effects of varying rates of N, P and K on potato tuber yield and yield components. The experiments were laid out using randomized complete block design with factorial arrangement, with four replicates. Factors were N rates (N_X) i.e N_1-0 kg ha^{-1}, N_{2} – 50 kg ha^{-1}, N_{3} – 100 kg ha^{-1} ; P_2O_5 rates (P_X) i.e P_1-0 kg ha^{-1}, P_{2} – 50 kg ha^{-1}, P_{3} – 100 kg ha^{-1}and K_2O rates (K_x) i.e K_1- 0 kg ha^{1}and K_2- 50 kg ha^{-1}. Number of tubers per plant, fresh tuber weight, small tuber yield, medium tuber yield, large tuber yield and total tuber yield were measured. Analysis of variance, performed using SAS-version 9.2, revealed that interaction effects of N×P×K were very highly significant on all parameters. Generally, $N_3 \times P_3 \times K_2$ performed better than other treatments and recorded highest tuber yields in all situations: (32.73 ± 0.43) t ha^{-1}[L_1] and (29.36 ± 0.41) t ha^{-1} [L_2] and (31.05 ± 0.52) t ha^{-1}for pooled ANOVA. Contrarily to what happened at L_2, $N_3P_3K_2$ and$N_2P_3K_2$ were not significantly different at $L_{1.}$ $N_2P_3K_2$ is recommended to L_1 whereas $N_3P_3K_2$ is recommended to L_2.

Key words: Potato, N-P-K nutrients, location-specific fertilizer recommendation, Rwanda.

Appendix 14: Scientific contribution of the current study/ Article published

Title of the paper: Assessment of soil fertility in smallholder potato farms in Rwanda

Journal: Agricultural Science Digest

Authors: Adrien Turamyenyirijuru[1&3], Guillaume Nyagatare [2], Robert Morwani Gesimba [3] and Rhoda Jerop Birech[3]

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Abstract

This study assessed soil fertility in potato farms of Birunga and Buberuka highlands agro-ecological zones (AEZs). It compared nutrients levels (N, P, K, Mg, Ca, Na, S, Mn, Cu, Zn and Fe) and other parameters (pH, organic carbon [OC], cation exchange capacity [CEC], base saturation [BS], bulk density [BD] and texture) of soil samples. ANOVA revealed that pH (5.53-6.50) varied from slightly to moderately acidic, BD fell below optimum (< $1.8 gcm^{-3}$), texture was sandy loam or sand clay loam. Soil fertility for OC (3.33-5.53%), N (0.15-0.31%) and CEC (10.08-18.60 meq/100g) varied from low to medium; and medium to high for BS (34.78-61.91%); was qualified medium for P (5.75-9.20 ppm), K (0.21-0.54 meq/100g), S (8.40-6.46 ppm) and majority of micronutrients. Values from Birunga AEZ were higher than ones from Buberuka AEZ except for BD, CEC, clay, silt, Na and Fe, Birunga AEZ was comparatively more fertile than Buberuka AEZ.There were significant differences between farms within locations for all parameters, and significant differences between locations for all parameters except Na and Mn.

Key words: Potato, soil fertility, Physical and chemical properties, Rwanda.

Appendix 15: Scientific contribution of the current study/ Article accepted

Title of the paper: Assessment of the Relationship Between Soil Reaction, Organic Carbon and other Soil Chemical Attributes in Potato farms in Rwanda

Journal: Bulgarian Journal of Agricultural Science

Authors: Adrien Turamyenyirijuru[1&3*], Guillaume Nyagatare[2], Robert M. Gesimba[3] and Rhoda J. Birech[3]

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ABSTRACT

Soil reaction (pH) and organic carbon (OC) emerged as governors and more indicative of soil properties and fertility. They govern various soil properties and processes in the soil. Despite potato yield potential, its yield remains low in Rwanda due to the decline in soil fertility and ineffective use of fertilizers. Nutrient deficiency and imbalance are major constraints to productivity and sustainability of soils. This study evaluated the relationship between soil pH as well as OC with other soil properties (N, P, Ca, Mg, K, CEC, S, Cu, Fe, Mn and Zn), in potato farms of Birunga and Buberuka highlands agro-ecological zones of Rwanda. Descriptive statistical parameters were calculated, using SAS Version 9.2 statistical software, for the selected soil attributes and their mean values varied from low to medium. The significance of correlation was determined by Pearson's correlation coefficient analysis. There was very high and significant positive correlation ($p < 0.001$) between OC as well as pH and all selected soil attributes. Factor analysis extracted two factors from observed variables and ratings of factor loadings were qualified strong (> 0.75) and moderate (0.50 to 0.75) at each site. The two latent variables were related to either inherent or dynamic soil properties. The results revealed pH and OC as shapers of soil chemical properties and fertility; there is a need for them to be the pillars of any optional technology developed to enhance soil fertility and productivity in the research areas. Adoption of site specific nutrient management practices is recommended for rational soil nutrients management and land utilization.

Key words: Potato farm-Soil properties-Correlation.

Appendix 16: Scientific contribution of the current study/ Article under review

Title of the paper: Potato (Solanum tuberosum L.) growth and tuber yield response to different levels of Nitrogen, Phosphorus and Potassium in Rwanda

Journal: Indian journal of agricultural Sciences

Authors:Adrien Turamyenyirijuru[1&3], Guillaume Nyagatare [2], Robert Morwani Gesimba [3] and Rhoda Jerop Birech[3]

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Abstract

Despite potato yield potential, its intensification levels remain low in Rwanda, translating into low yield occasioned mainly by the decline in soil fertility. Field experiments were conducted in Birunga, Mudende [L1]) and Buberuka, Rwerere [L2] highlands Agro-Ecological Zones (AEZs), during season A 2017 and B 2017 to determine the effects of varying rates of N, P and K on growth and yield of potato. The experiments were laid out using a Randomized complete block design with factorial arrangement, with four replicates. Factors were N rates (N_X); (i) N_1-0 kg ha^{-1}, (ii) N_{2} – 50 kg ha^{-1} (iii) N_{3} – 100 kg ha^{-1} ; P_2O_5 rates (P_X); (i) P_1-0 kg ha^{-1}, (ii) P_{2} – 50 kg ha^{-1} (iii) P_{3} – 100 kg $ha^{-1}$and K_2O rates (K_x); (i) K_1- 0 kg $ha^{1}$and (ii) K_2- 50 kg ha^{-1}. Stem height, number of main stems per plant, Leaf area index and tuber yield were measured. Analysis of variance, performed using SAS-version 9.2, revealed that interaction effects of N×P×K were non-significant on number of main stems per plant and very highly significant on all other parameters. Generally, $N_3 \times P_3 \times K_2$ performed better than other treatments and recorded highest tuber yields in all situations: (32.73 ± 0.43) t ha^{-1}[L_1] and (29.36 ± 0.41) t ha^{-1} [L_2] and (31.05 ± 0.52) t $ha^{-1}$for pooled ANOVA. Contrarily to what happened at L_2, $N_3P_3K_2$ and$N_2P_3K_2$ were not significantly different at $L_{1.}$ N_2P_3 K_2 is recommended to L1 whereas $N_3P_3K_2$ is recommended to L_2. Further studies to determine optimum rates of N, P and K for potato performance in all the crop growing zones in Rwanda are needed.

Key words: Potato, N-P-K nutrients, Precision Agriculture, Rwanda.

Appendix 17: Research Licence

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Appendix 18: Research Publication

RESEARCH ARTICLE

Potato (*Solanum tuberosum L.*) Tuber Yield and Yield Components as Influenced by Different Levels of Nitrogen, Phosphorus and Potassium in Rwanda

Adrien Turamyenyirijuru[1,3], Guillaume Nyagatare [2], Robert Morwani Gesimba [3], Rhoda Jerop Birech[3]

10.18805/ag.D-155

Abstract

Despite potato yield potential, its intensification level remains low in Rwanda, translating into low yield occasioned mainly by the decline in soil fertility. Field experiments were conducted in Birunga, Mudende [L_1]) and Buberuka, Rwerere [L_2] highlands Agro-ecological zones (AEZs), during September to December 2016 and March to June 2017 crop growing seasons to determine the effects of varying rates of N, P and K on potato tuber yield and yield components. The experiments were laid out using a randomized complete block design with a factorial arrangement, with four replicates. Factors were N rates (N_x) i.e N_1-0 kg ha^{-1}, N_2 _ 50 kg ha^{-1}, N_3 _ 100 kg ha^{-1} ; P_2O_5 rates (P_x) i.e P_1-0 kg ha^{-1}, P_2 _ 50 kg ha^{-1}, P_3 _ 100 kg ha^{-1}and K_2O rates (K_x) i.e K_1- 0 kg ha^{-1}and K_2- 50 kg ha^{-1}. Number of tubers per plant, fresh tuber weight, small tuber yield, medium tuber yield, large tuber yield, and total tuber yield were measured. Analysis of variance, performed using SAS-version 9.2, revealed that interaction effects of N×P×K were very highly significant on all parameters. Generally, $N_3P_3K_2$ performed better than other treatments and recorded highest tuber yields in all situations: (32.73 ± 0.43) t ha^{-1}[L_1] and (29.36 ± 0.41) t ha^{-1} [L_2] and (31.05 ± 0.52) t ha^{-1}for pooled analysis of variance (ANOVA). Contrarily to what happened at L_2, $N_3P_3K_2$ and $N_2P_3K_2$ were not significantly different at L_1. N_2P_3 K_2 is recommended to L_1 whereas $N_3P_3K_2$ is recommended to L_2.

Key words: Potato, N-P-K nutrients, location-specific fertilizer recommendation, Rwanda.

Agricultural Science Digest (2019)

Introduction

Agriculture accounts for one-third of Rwanda's gross domestic product (GDP), and the sector is, however, characterized by low productivity resulting from soil fertility decline over the years, which primarily results from continuous cultivation without adequate addition of external nutrient inputs (MINECOFIN, 2012). In permanent agricultural systems, soil fertility is maintained through the application of organic and mineral fertilizers (IFDC, 2009), their application varies across locations and seasons due to difference in soil types, nutrient availability of the soil, moisture supply and variety (Zelalem *et al.*, 2009).

Potato is an important crop for food and income generation in Rwanda; its cultivation is intensively carried out year-round in Birunga and Buberuka highlands AEZs where weather and soil conditions are potentially favorable for the crop performance (MINAGRI, 2011). Potatoes are heavy feeders, and therefore require adequate and balanced quantities of nutrients throughout their growth period (Zelalem *et al.*, 2009). In Rwanda, the crop is mainly grown by smallholder farmers who realize only about 10.2 t ha^{-1} compared to the potential yield of 40 t ha^{-1} (MINAGRI,2011). Low soil fertility occasioned by continuous cultivation coupled with Inefficient addition of external nutrient inputs is a major constraint, affecting growth and tubers yield (MINAGRI, 2004). Nitrogen, phosphorus, and potassium are the major macronutrients in agro-ecosystems, therefore are the first to limit potato crop production (Jenkins and Mahmood, 2003). The fertilizer recommendation prevailing in Rwanda is general (blanket); 300 kg of compound fertilizer 17-17-17 ha^{-1} and does not consider heterogeneity in the soil at a landscape level. The general application of fertilizers leads to soil fertility decline, thus impeding potato

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