IMPACT OF MULCH AND FERTILIZER APPLICATION ON YIELD COMPONENTS, TUBER QUALITY AND THE NUTRIENT UPTAKE OF SELECTED POTATO CULTIVARS UNDER IRRIGATED CONDITIONS

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DECLARATION

I, Ntuli Jabulani, hereby declare that, to the best of my knowledge, the work presented in this dissertation entitled “Growth, yield and nitrogen use efficiency responses of various potato cultivars to integrated nutrient management centered on fertilizer and mulch application” is my original work and it has never been presented by anyone in any academic institution for the award of Master of Science in Agriculture (Agronomy) or any other academic qualification. This dissertation does not contain other persons’ data, pictures, graphs or other information (e.g., texts, tables etc.) unless specifically acknowledged as being sourced from other persons. The ideas of other authors or scholars cited in this document have been profusely acknowledged.

19/02/2024

MR J NTULI (Candidate) Date

We, as the candidate’s supervisors, have/~~have not~~ approved this dissertation for submission.

19/02/2024

DR ST HADEBE (Supervisor) Date

19/02/2024

PROF NZ NGOBESE (Co-Supervisor) Date

DEDICATION

Every difficult task requires self-effort and guidance from God and others, particularly those who hold a special place in our hearts. I dedicate my humble efforts to the Almighty God. Additionally, I dedicate this work to my supporting and loving parents (Mr Ntuli Mosebenzi Moses and Mrs Ntuli Ntombezane Betty), sisters (Ms Ntuli Nomsa Patience, Ms Ntuli Nicol Patricia, and Ms Ntuli Beauty Kisten), brother (Mr Skosana Vincent Sana), and everyone who contributed to the success of this work.

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TABLE OF CONTENTS

Contents page

LIST OF FIGURES

LIST OF TABLES

PREFACE

This mini-dissertation aimed to assess the potential of integrating cultivar selection, soil cover and judicious application of nutrients to reduce the soil fertility-based potato yield and nutritional gap. This was broken down into five interlinked chapters. Chapter one provides a general background on poor fertilizer application and management, nutrient losses and poor cultivar selection as potential contributors to poor soil fertility in the Limpopo province of South Africa. Poor soil fertility is then linked to reduction of tuber yield, quality and nutrition in potatoes. Chapter two consists of a detailed literature review of integrated nutrient management as a strategy to reduce excessive use of inorganic fertilizers. The literature review identifies the contribution of, and gaps in applying integrated nutrient management strategies for potato yield and quality improvement. Chapter three provides a detailed experimental response of potato phenological development, biomass accumulation, and tuber yield to integrated nutrient management centered on cultivar selection, fertilizer application rates and soil cover using mulch. In Chapter four, tuber nutritional and grading quality from tuber harvest from chapter three is presented to showcase the impact of integrated nutrient management on tuber quality. Additionally, the efficiency to utilize nitrogen is interrogated to assess the potential of integrated nutrient management on reducing nitrogen losses and increasing crop nitrogen uptake. Chapter five provides a general discussion and conclusion of findings from chapter two, three, and four with the view of addressing the study's overall aim. This chapter also provides recommendations on applicability of the study results, and future research that can be conducted to promote integrated nutrient management as a potato yield and quality improvement strategy.

ABSTRACT

Integrated nutrient management (INM) in potato production is a promising mitigation strategy to reduce the nutrient-related yield gap. Potato yield and quality are limited in Limpopo by poor soil fertility. This problem is caused by a combination of poor fertilizer application and management, high temperatures and soil degradation. Reductions in potato yields in this region are leading to nationwide potato shortages and price increases. Previous research has shown that INM can maximize potato yield, tuber quality, and limit nutrient losses without degrading the quality of the soil. Therefore, in the present study, INM was centered on fertilizer and mulch application to evaluate growth, yield and nitrogen use efficiency (NUE) responses of various potato cultivars. A field trial was conducted in spring season from September 2022 to February 2023. Four potato cultivars (Mondial, Sababa, Panamera, and Tyson) were evaluated at three fertilizer application rates (0%, 50%, and 100% of the recommended fertilizer application rates from soil test) and two soil cover levels (lucerne grass mulch and no mulch). The selected potato cultivars differed in the potential yield, crop canopy, and time to maturity. These treatments were laid-out as split-split plot in a randomized complete block design replicated three times. For tuber quality and NUE, the experiment was carried out as 3 x 2 x 4 factorial layout, arranged in a completely randomized design (CRD). During the growing season, phenological development and canopy cover were recorded. At and post-harvest, shoots and root biomass, tuber number, fresh mass, dry matter, size grading, and NUE were recorded.

Significantly higher tuber yields (41.29 t/ha) were obtained from Panamera cultivar when mulch was applied with the combination of 50% recommended fertilizer application rates. This treatment combination yielded comparable tuber yields as that of 100% recommended fertilizer application rates, mulching and the Panamera cultivar. This suggests that it is possible for farmers to reduce fertilizer application from the recommended rates without compromising their potato yields. Significantly higher NUE (72%) was obtained from Panamera cultivar when mulched without the application of fertilizer. The findings of the study indicated that NUE decreases linearly with increasing N application. The application of 50% fertilizer recommended rate had a significantly higher NUE (31.28%) than 100% recommended fertilizer application rate (19.78%). Very low NUE under 100% recommended N rates indicated that fertilizer saturated states tend to lose more nutrients than unsaturated states. The lowest potato yields (approx. 27 t/ha) were produced by Tyson across all fertilizer levels and Mondial at 50% fertilizer application rate. Mulching increased potato yield by approximately 8 and 16 t/ha under 0 and 50% fertilizer application rates respectively. Generally, mulching induced a significant increasing on time taken to reach physiological maturity, biomass accumulation, tuber fresh mass, number of tubers, and large sized tubers.

Across fertilizer treatments, 100% fertilizer application rate significantly increased the shoot dry biomass by 1.39 t/ha relative to 0% fertilizer application rate. Generally, application of 100% fertilizer recommended rate on potato fields resulted in significantly high canopy cover, shoot dry biomass and tuber fresh mass. Potato fields where fertilizers and mulch were not applied, produced significantly lower canopy cover (60.42%) and number of tubers (5.83/ plant). Additionally, secondary interaction of Panamera and Mondial with mulch application showed significantly higher shoot dry biomass (5 t/ha). Growth, quality and yield components of the selected cultivars varied significantly, with Panamera being found to outperform other cultivars. These results suggest that almost the same economic yields can be achieved by applying half the recommended fertilizer rates and using mulch to prevent soil water and nutrient losses. Panamera integrated with 50% fertilizer application rate and mulch application is suitable for sustainably optimizing tuber growth and yield in potato farming. However, the study's findings were limited to environmental conditions prevailing in the study area, single planting season, and hail crop damage. Future research must therefore look at the studied INM in different hail-free seasons and locations.

Keywords: fertilizer rates, growth, mulching, nitrogen use efficiency, poor soil fertility, potato cultivar, tuber quality, yield

CHAPTER 1: GENERAL INTRODUCTION

1.1 Problem statement

Farmers across South Africa are subjected to poor soil fertility, which is the major cause of poor quality and low yields of potatoes (*Solanum tuberosum* L.) (Mdoda *et al*., 2023). The Limpopo province is the largest producer of South Africa's potatoes, and any factor that lowers yields in the province usually results in a countrywide potato shortage and an increase in prices (van der Waals *et al*., 2013). Poor soil fertility of some agricultural soils in the Limpopo province can be attributed to high levels of soil degradation, poor fertilizer application and management, high temperatures that increase soil evaporation and loss of nitrogen through volatilization (Odhiambo and Nemadodzi, 2008; Molepo *et al*., 2016; Materechera and Scholes, 2021). Soil degradation is a result of continuous cultivation that reduces the organic matter in the soil, which further causes poor soil fertility (Pepper *et al*., 2019). This is worsened when there is no adequate replenishment of mined nutrients due to relatively high cost of fertilizers which usually limits fertilizer application, particularly by smallholder farmers (Mpandeli and Maponya, 2014). The Limpopo province lacks soil testing facilities, and available facilities are distant and overbooked, further discouraging soil testing by farmers. This contributes to incorrect fertilizer application by potato farmers (Kom *et al*., 2020). The prevalence of coarse, textured soils with low cation exchange capacity (CEC) and low water holding capacity (WHC), together with hot temperatures in the Limpopo province, increase nitrogen volatilization during potato growing seasons (Jones *et al*., 2013; van der Waals *et al*., 2013; Siman *et al*., 2020). Smallholder farmer potato yields, and tuber nutritional quality can be low as these farmers are prone to planting non-certified potato seeds due to financial constraints (Andiku *et al*., 2021). One possible solution to counteract the effects of soil degradation, high temperature, and dry conditions in Limpopo is to incorporate mulch application practice. Organic mulching improves soil fertility by adding significant amounts of organic matter and slow-release nutrients, thereby improving soil fertility (Ramineh *et al*., 2023). Mulching moderates soil temperature during hot weather (Wang *et al*., 2003) and increases crop yield through improving soil moisture retention (Lin *et al*., 2015). This reduces the loss of nutrients through volatilization. Mulching maintains soil moisture (Chen *et al*., 2019) by improving infiltration and reducing surface runoff and soil erosion. It is also important for these farmers to select the best cultivar that is adapted to the Limpopo planting areas and consider the planting season to ensure high potato productivity and lower vulnerability to nutrient stresses. Compared to large-scale farmers (who produce an average yield of 51.25 kg/ha), small-scale farmers produce an average yield of 4.9 kg/ha (Franke and Sekoboane, 2020), and a particular portion of this yield gap is attributed to poor soil fertility which reduces the yield and quality of potatoes. It is projected that potato yields may drop by 20 to 40 % due to a lack of adaptation strategies to future conditions in Africa (Romero *et al*., 2017), where nutrient-related losses form a considerable part of that projected yield gap. It is therefore critical for farmers to develop integrated soil fertility management strategies that optimize soil fertility and enhance tuber yield and potato tuber quality in South Africa and the African continent.

1.2 Motivation

Soil nutrient deficiencies have a negative effect on potato growth, tuber yield, and tuber quality. Farmers usually grow cultivars that are popular in the markets (e.g., Mondial and BP1). Sometimes cultivars bred for adaptability to certain regions can easily be overlooked (van Niekerk *et al*., 2016). Planting cultivars that do not optimize nutrient uptake can exacerbate issues of reduced potato nutrient uptake and nitrogen use efficiency in regions like Limpopo, where climatic and soil conditions favour volatilization and leaching of nutrients (Zebarth *et al*., 2004; van der Waals *et al*., 2013). The negative effects of farmers preferring popular cultivars tend to primarily affect newly released cultivars that are not established/known in the markets. Furthermore, less than optimal nutrient management practices (e.g., incorrect fertilizer application by some farmers, and lack of soil cover) worsen usage efficiency of applied fertilizers (Siman *et al*., 2020). Understanding the uptake efficiencies of different potato cultivars is important as it makes it possible for farmers to select the most profitable cultivar that have lower production costs associated with fertilizer application. Integration of soil cover practices (such as mulching), correct fertilizer application, and suitable cultivar selection by potato farmers can potentially enhance soil fertility and potato nutrient uptake; thereby ensuring sustained potato high yields and yield quality preferred by potato markets (Khan *et al*., 2012; Reema *et al*., 2020). This integration of various fertility management strategies aimed at retaining soil nutrients and optimizing crop nutrient uptake can alleviate household food insecurity and contribution to potato production to South Africa's gross domestic product through increased agricultural production (Pawlak and Kołodziejczak, 2020; Franke and Sekoboane, 2021). To our knowledge, no scientific literature to date has reported on integrating cultivar selection, usage of organic mulch and application of different fertilizer rates in order to reduce the nutrient-inspired yield gap in potatoes. This knowledge is particularly critical for a production region like Limpopo, where temperatures are projected to increase, and where recently improved cultivars suited for regional production have been released (van der Waals *et al*., 2013). These necessitate a field trial testing performance of selected potato cultivars and their responses to mulch and fertilizer application at various rates.

1.3 Aim

This study aims to assess the potential of integrating cultivar selection, soil cover and judicious application of nutrients to reduce the soil fertility-based potato yield and nutritional gap. This aim is broken down into two objectives:

1.3.1 Objectives

II. Objective 1

To investigate the interaction effect of potato cultivar selection and grass mulch application under varying soil fertility levels on potato growth and yield under irrigated conditions.

III. Objective 2

To determine the interaction effect of potato cultivar selection and grass mulch application under varying soil fertility levels on potato tuber quality and nitrogen use efficiency under irrigated conditions.

1.3.2 Null Hypotheses

I. Hypothesis 1

Potato cultivar selection and grass mulch application under varying soil fertility levels will not affect potato growth and yields under irrigated conditions.

II. Hypothesis 2

Potato cultivar selection and grass mulch application under varying soil fertility levels will not affect potato tuber quality and nitrogen use efficiency under irrigated conditions.

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CHAPTER 2: INTEGRATED NUTRIENT MANAGEMENT AS A STRATEGY TO REDUCING EXCESSIVE USE OF INORGANIC FERTILIZERS IN POTATO FARMING – A LITERATURE REVIEW

2.1 Introduction

Potato (*Solanum tuberosum* L.) is one of the most important agricultural crops and ranked 4th in Africa after wheat, maize and rice in terms of consumption (Zhang *et al*., 2017; Ahmadu *et al.,* 2021). The current potato yields in Africa are unsustainable and vary widely, ranging from 0.7 to 36 t/ha, with a continental average of 13 t/ha (Chifetete and Danes, 2020). The major causes of low potato productivity in Africa are poor adoption of improved varieties and nutritionally depleted soils (Van der Waals and Krüger, 2020; Muthoni and Shimelis, 2023). Soil fertility depletion is an important concern directly linked to food insecurity in developing and least developed countries due to the intensification of land use for agricultural production without proper application of external inputs (Tan *et al.,* 2005). Soil nutrient depletion can be attributed to unbalanced fertilization, over-cultivation, accelerated soil erosion caused by continuous loss of soil organic matter (SOM) and decline in soil structural stability, and poor soil management practices (Tan *et al.,* 2005; Aleminew and Alemayehu, 2020).

The decline of soil organic matter, which also plays a central role in soil health or quality poses a serious threat to sustainable agriculture in Africa (du Preez *et al.,* 2011). Low SOM has a significant impact on soil nutrient losses, leading to reduced soil fertility and decreased crop yields. Over time, as SOM decreases, soil quality not only deteriorates in terms of reduced aggregate stability, soil C storage and water holding capacity, but also the soil's ability to hold nutrients (Stark and Porter, 2005; Singh, 2018). Long term monoculture and continuous conventional cultivation of potatoes in sandy loam soils, where nutrients are easily lost beyond the root zone (Zelalem *et al.,* 2009; Xu *et al*., 2022), further exacerbate nutrient depletion through reducing SOM and soil biological activity. Such changes can influence nutrient cycling and crop mineral uptake (Montgomery and Biklé, 2021).

To overcome the impact of poor soils and increase potato yields, farmers have been applying inorganic fertilizers in excessive and disproportionate quantities. However, reported fertilizer use by potato farmers does not reflect expected productivity levels as low yields are still reported in farmers' fields (Mugo *et al*., 2021). Excessive use of inorganic fertilizers is often associated with reduced yield, soil acidity, and nutrient imbalance (Dunsin *et al*., 2019; Blecharczyk *et al*., 2023). Continuous application of excessive amount of inorganic fertilizers increases the cost of production while causing many environmental problems such as desertification of lands, loss of soil biodiversity, and eutrophication that occurs a result of increased leaching of nutrients (Ariyapala and Nissanka, 2006; Thakur and Kumar, 2020). Inorganic fertilizers further obstruct the breakdown of SOM and alters nutrient cycling through reduced microbial activity, pH reduction, and depletion of soil nutrients (Mahal *et al*., 2019; Hlisnikovský *et al.,* 2021).

The large differences in the yield and application of inorganic fertilizers reflect the management gap between optimal crop nutrient management practices and farmer’s practice (Xu *et al*., 2022), and suggest that there is large gap for improving potato yields in Africa without increasing the already high fertilizer application rates. Research findings have shown that neither mineral fertilizers nor organic sources alone can result in sustainable productivity (Atanaw and Zewide, 2021). Therefore, the best potential remedy for poor soil quality is combined judicious application of NPK fertilizer, organic mulch and suitable cultivar selection, which is essential for maintaining high yields, better tuber quality and more profit, as well as improving the physicochemical properties of the soil. This integrated nutrient management is an essential tool for balanced fertilization and sustainability of potato production on long term basis. The aim of this review is to review the literature on integrated nutrient management to optimize potato growth and tuber yield and to improve productivity of soil physicochemical properties.

2.2. Potential causes of nutrition-related problems in potatoes

2.2.1 *Poor management practices*

Excessive inorganic fertilizer application

Worldwide mineral fertilizer consumption is steadily increasing in response to the growing population and increased demand for food and non-food crops (Huang *et al*., 2017). Additionally, the phenomenal decline in nutrient use efficiency of various crops and cropping systems has gradually prompted farmers to apply higher amounts of nutrients. For instance, the total N, P and K use per area of cropland in South Africa increased from 26.37, 11.85 and 8.71 kg/ha, in 2000 to 44.86, 25.29 and 20.89 kg/ha, (Figure 2.1) respectively, in 2021. Over 40 years, the amount of mineral N fertilizers applied to agricultural crops increased by 7.4-fold, whereas the overall yield increase was only 2.4-fold (Hirel *et al*., 2011). This suggests that NUE is higher at reduced levels of crop production when the use of N fertilization is much lower. Many other studies have reported that NUE decreases linearly with increasing N application (Darwish *et al*., 2006; Fontes *et al*., 2010; Mustonen *et al*., 2010; Nieto, 2016). As a result, this injudicious nutrient management practice has paved the way to degrade soil quality due to less or no use of organic manure and residue retention (Paramesh *et al*., 2023). In addition to significantly increasing greenhouse gas emissions, high-input agricultural practices have destroyed vast amounts of soil and water resources in the agro-ecosystem and deteriorated soil quality (Paramesh *et al.,* 2023). Among agricultural practices, nutrient management is one such practice that plays a critical role in crop productivity and soil health.

Inorganic fertilizer is the main source of nutrients for potato cultivation. However, continuous application of inorganic fertilizer causes nutritional imbalance and adverse effects on soil physicochemicals and biological properties (Pandit *et al*., 2018; Singh *et al.,* 2018). Long-term excessive use of chemical fertilizers can result in several problems such as reduced SOM content, with a consequent decline in the agricultural soil quality through soil nutrient losses, poor water holding capacity, and reductions in microbes, and even increase surface water and groundwater pollution, and soil acidification or basification (Demelash *et al*., 2014; Ning *et al*., 2017; Sharma, 2017;

Abebe *et al.*, 2022). The number of aggregates reflects the soil's ability to supply and store nutrients (Le Bissonnais, 2016). The rate of soil aggregate destruction correlates with organic matter content (i.e., high organic matter content is associated with low rates of aggregate destruction) (Liu *et al*., 2014), therefore reducing SOM leads to a low soil aggregate stability and cation exchange capacity. Excessive use of chemical fertilizers can affect the accumulation of heavy metals in the soil and plant system (Savci, 2012). Over-fertilization increases production costs by about 33% and greenhouse gas emissions by 60%, and also reduces yields by about 15–18% (Rahman and Zhang, 2018). Due to the use of ammonium fertilizers and the leaching of cations from the root zone, many soils now utilized for the production of potatoes have become more acidic over time (Li *et al*., 2018a; Gao *et al*., 2022; Gelaya, 2023).

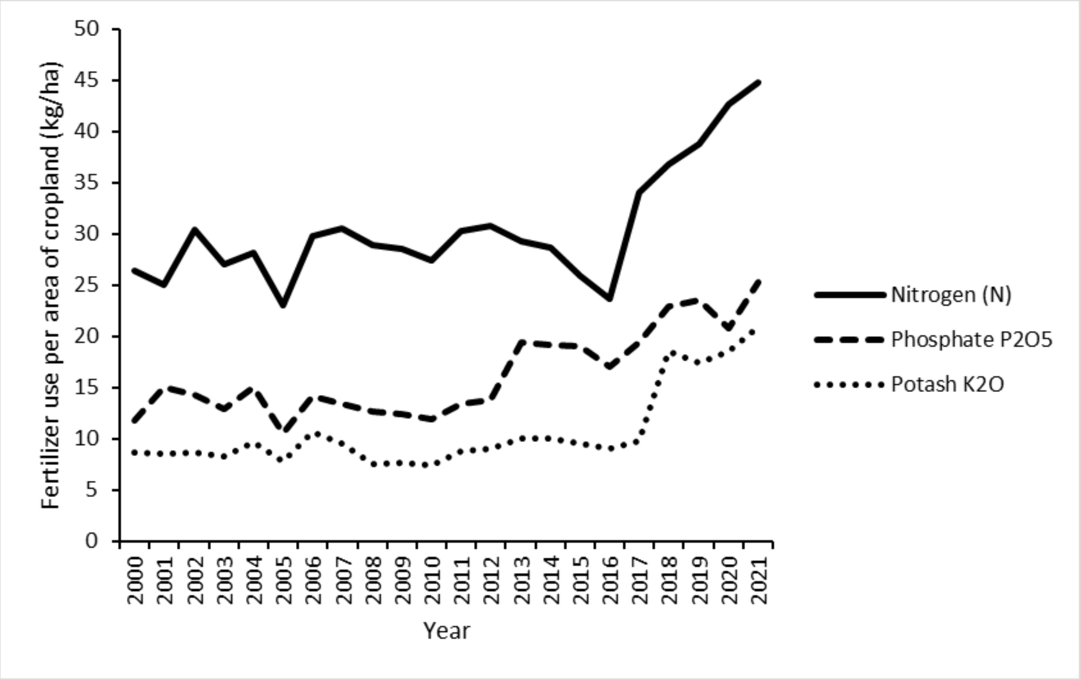

Figure 2.1: Annual fertilizer use per area of cropland from 2000 to 2021 in South Africa (FAOSTAT, 2023).

Choice of cultivar

Different potato cultivars require different amounts of nutrients based on their genetic makeup, growth habits, and yield potential. However, most farmers do not consider such differences for the cultivars that they grow. Uniform fertilization without taking these differences into account can lead to an imbalance of nutrients in the soil. Most commercial potato cultivars are grown with high N fertilizer levels combined with irrigation, which leads to a large reduction of NUE and contributes greatly to N leaching and ground water contamination under sandy soils (Zebarth *et al*., 2004; Ospina *et al.,* 2014; Getahun *et al.*, 2020). Nitrogen fertilizer input cannot be fully utilized, and the nitrogen use efficiency of potatoes has long been between 30% and 35% (Liu *et al*., 2023). This suggests that more than half of the applied N is lost in the environment, translating into reduced NUE. Half of the applied N is usually lost through NO_3^- leaching, denitrification, or ammonia volatilization (Chattha *et al*., 2022). These issues are exacerbated by the poorly developed potato root system which is often characterized as shallow and inefficient, with poor ability to extract water and minerals from the soil (Joshi *et al*., 2016), although this varies between cultivars.

Certain cultivars can be more efficient at absorbing specific nutrients from the soil. Applying excessive fertilizer to these cultivars can result in excess nutrients that go unutilized by the plants and subsequently leach into the soil or water bodies. Differences in NUE under high and low N input regimes is strongly related to maturity of the cultivars (Tiemens-Hulscher *et al*., 2012). NUE in late maturing potato cultivars is higher compared to early maturing cultivars and this is ascribed to the higher canopy development tendency in late maturing cultivars, which results in a longer period of light interception and is closely associated to high total dry matter accumulation in the tuber (Zebarth *et al*., 2004; Ospina *et al*., 2014; Getahun *et al*., 2020). By optimizing nutrient use efficiency and precise fertilizer application and management according to the specific nutrient requirements of different potato cultivars, it is possible to achieve high potato yields while minimizing the risk of soil nutrient imbalances.

2.2.2 Climate

Currently as a result of climate change, and uneven rainfall distribution and fluctuations, the risk of water and nutrient stress in potatoes is greater (Jama-Rodzenska *et al.*, 2021). Such impacts of climate change will be particularly noticeable in the warmer regions covering most developing countries and the yield will decrease by 20–40% in the future (FAOSTAT, 2018). Changes in climatic factors such as precipitation intensities or seasonal temperatures can greatly influence plant nutrient uptake and availability from the soil. In most intensive agricultural production systems, over 50% and up to 75% of the N applied to the field is not used by the plant and is lost to environment by pathways such as leaching or volatilization (Hirel *et al*., 2011; Gao *et al*., 2018). Such losses reduce NUE in agricultural production systems. Ammonium, a common form of nitrogen in soils can be converted into ammonia gas and released into the atmosphere at elevated temperatures (Jones *et al*., 2013). This can lead to a loss of available nitrogen for plant uptake and growth, which can negatively impact crop yields and ecosystem health. Soil temperature controls gaseous nitrogen losses through nitrous oxide (N_2O) and ammonia (NH_3) fluxes (Chatterjee *et al*., 2020). Generally, the risk of NH_3 volatilization is increased at soil temperatures over 21.11°C, while nitrification is most rapid when soil is warm (19.44 - 30 °C), moist and well-aerated (Khajuria and Kanae, 2013; Dari *et al*., 2019).

High temperatures not only cause volatilization but can also accelerate microbial activity and decomposition in the soil. While some decomposition is necessary for nutrient cycling, excessive heat can cause organic matter to break down too quickly, potentially leading to reduced nutrient availability (Onwuka, 2016). Soil temperature between 21 and 38°C increases organic matter decomposition by increasing the movement of soluble substrates in the soil and stimulating microbial activities (Fang *et al*., 2005; Fierer *et al*., 2005; Broadbent, 2015). An increase in temperature by 1°C could ultimately lead to a loss of over 10% of soil organic carbon (SOC) in soils with temperature of 5°C, whereas the same temperature increase would lead to a loss of only 3% of SOC for a soil at 30°C (Kirschbaum, 1995). Loss of SOM due to increased decomposition rate or soil erosion can increase bulk density and lead to soil compaction (Gelybo *et al*., 2018), with consequences such as decreasing porosity and compact layer formation which can reduce nutrient uptake through inhibiting root growth.

2.2.3 Soil physicochemical properties

Soil physical and chemical properties play a crucial role in determining soil fertility for potato cultivation. Potatoes are mostly grown on well-drained, coarse-textured soils with low organic matter content (<2%), which further increase the risk of N loss through leaching and runoff particularly when there is excess rainfall (Rens *et al.*, 2016; Rawal *et al*., 2023). Sandy soils have low cation exchange capacity (CEC) (Bi *et al*., 2023), meaning they have a limited ability to retain and exchange nutrients. Therefore, nutrients, particularly nitrates, can easily be washed away by excessive rainfall or irrigation, leaving the root zone and depriving plants of essential nutrients. Sandy soils typically have low nutrient retention and 20-80% of applied nutrients or chemicals are leached or runoff to ground and surface waters (Matichenkov *et al*., 2020). Conventional potassium (K) fertilizers (KCl, K_2SO_4 or K_2CO_3) and nitrogen in the form of nitrate (NO^{3-}) are highly soluble, and consequently a significant amount of K and N can be lost through leaching (Alfaro *et al*., 2004; Matichenkov *et al*., 2020).

Potato production requires substantial soil disturbance due to the need for planting, hilling, and harvesting of this below-ground crop (Rawal *et al*., 2023). This increases the risk of soil erosion, nutrient leaching and intensive soil tillage can accelerate the decomposition of crop residues by exposing them to increased oxygen levels and microbial activity (Reda, 2016). In addition, crop residues decompose more quickly in sandy soils compared to finer-textured soils. Therefore, N released residues after harvest may be leached out before it can be utilized by the subsequent crop, resulting in a reduction in available N to crops (Rawal *et al*., 2023).

When organic matter content is low, CEC is reduced (Zuza *et al*., 2023), limiting the soil's ability to hold on to essential nutrients, making them more susceptible to leaching or unavailable to plants. Soils low in organic matter have reduced water-holding capacity, leading to poorer water retention and increased vulnerability to drought stress, resulting in loss of fertility and increased emissions of greenhouse gases (Ayangbenro and Babalola, 2021). Low organic matter content also limits microbial population and activity, disrupts nutrient cycling processes, and impairs crop residue breakdown (Kibblewhite *et al*., 2008; Naylor *et al*., 2022). Without sufficient organic matter, soils are more susceptible to pH fluctuations, which can impact nutrient availability (Gurmu, 2019). Soil pH has a profound impact on soil fertility and overall soil quality. It affects nutrient availability, microbial activity and chemical reactions that occur in the soil (Zhao *et al*., 2011; Wang *et al*., 2019a). In highly acidic soils, aluminum and manganese may become more available and more toxic to plants, while calcium, phosphorus, and magnesium may become less available to the plant, and in highly alkaline soils, phosphorus and most micronutrients may become less available (Sumner and Yamada, 2002; Rahman *et al*., 2018; Sirisuntornlak *et al*., 2021).

2.3. Effect of mineral nitrogen, phosphorus and potassium fertilizer on the growth and yield of potato

2.3.1 Nitrogen

Nitrogen (N) in the form of ammonium (NH_4^+) and nitrate (NO^{3-}) is one of the most vital macronutrients for growth and biomass development (Silva *et al*., 2013; Ayyildiz, 2021; Mustafa and Sevgi, 2021). It is an integral part of the chlorophyll molecule, and it combines with compounds of carbohydrate metabolism in the plant to form amino acids and proteins (Muleta and Aga, 2019). Optimal N nutrition contributes to the rapid formation of vegetative parts and influences canopy density and coverage (Oliveira, 2000; Nurmanov *et al*., 2019). Therefore, it has a positive effect on photosynthesis efficiency by increasing the interception rate of radiation and photons (Koch *et al*., 2020). Intercepted photosynthetically active radiation is a major determinant of total dry matter production and biomass accumulation of the potato crop and increases with increasing canopy cover (Nieto, 2016; Nkhase, 2019). Usually, the amount of N applied in potatoes varies between 100 and 300 kg/ha; the uptake rate increases during tuber bulking, but upon maturation, N uptake stops, plant senescence begins, and nutrients move from the foliage to the tubers (Koch *et al*., 2020; Mustafa and Sevgi, 2021).

Furthermore, N fertilization reportedly increases the yield and yield components of potato tubers. The increase in tuber weight due to fertilizer application could be due to more luxurious growth, more foliage and leaf area and higher supply of photosynthates which result in the production of larger tubers and hence higher yields (Sharma and Arora, 1987; Zewide *et al*., 2012; Getie *et al*., 2015). While N is an essential nutrient for plant growth, excessive application of N fertilizers beyond crops' demand, not only leads to undesirable consequences of degradation in soil, water and air quality but also lowers tuber yield. Excessive N supply leads to higher photosynthetic activity and vegetative growth at the expense of reproductive structures such as flowers and tubers, which is accompanied by weak stems, long internodes, droopy leaves, and increased susceptibility to lodging (Tsehaw, 2006; Workineh *et al*., 2017). Plants absorb only 40–50% of the total N applied and the remaining N is lost to the environment (Trehan and Singh, 2013), suggesting that excessive N application rates can lead to serious problems due to large N losses and low NUE.

2.3.2 Phosphorus

Phosphorus (P) is essential in many plant functions and is required in a stable supply to avoid disruptions in plant growth (Rosen and Bierman, 2008). The P fertilizer recommendation for potatoes varies depending on the P status of the soil and estimated yield. The amounts of P required in potato production are between 100 and 400 kg P/ha (Maier *et al*., 2002; Hopkins *et al*., 2014). Similar to N, the P requirement is rather low in the first weeks of growth, but in contrast to N, P is also absorbed in comparatively large quantities after tuber bulking during maturity phase. Its most important role is cellular energy transfer through dephosphorylation of adenosine triphosphate (ATP) to adenosine diphosphate (ADP) (Koch *et al*., 2020). Studies reported that phosphorus has various effects on vine growth, tuber formation, tuber bulking, and tuber quality because of its role in cell division and the synthesis and storage of starch in tubers (Fernandes *et al*., 2014; Hopkins *et al*., 2014; Nyiraneza *et al.*, 2017; Aarakit *et al*., 2021). Potato tuber yield is influenced by P fertilizer through its effect on the number of tubers produced, the size of the tubers, and the time at which maximum yields are obtained (Aarakit *et al*., 2021; Zewide and Atanaw, 2021; Qiu *et al.*, 2022). Although potato requires large amount of nutrients, particularly nitrogen, phosphorus, and potassium (NPK), the use efficiency of these nutrients is low due to shallow and inefficient rooting system of potato (Hopkins *et al*., 2014; Milroy *et al*., 2019; Gelaye *et al*., 2022). Hence these nutrients are often applied in excess amounts, consequently having detrimental effects on the environment (Koch *et al*., 2020; Tyagi *et al*., 2022).

2.3.3 Potassium

Potassium (k) is required in large quantities for optimum plant growth and productivity, because it is essential for completion of various physiological and metabolic functions in plants (Oosterhuis *et al*., 2014). In plant tissues, K is considered as the second most abundant nutrient after N and it is even more abundant than P (Torabian *et al*., 2021). The K uptake pattern follows a similar pattern to that of N with highest uptake during the tuber bulking stage (Stark *et al*., 2004; Horneck and Rosen, 2008). K is crucial for potato plant growth, cell growth maintenance, turgor pressure, leaf elongation, root elongation, photosynthesis and regulation of stomatal guard cells (Prajapati and Modi, 2012; Panthi *et al*., 2019; Torabian *et al*., 2021). It increases tuber bulking rate and duration, aids in carbohydrate translocation, and stimulates starch synthase for starch synthesis (Koch *et al*., 2020; Atanaw and Zewide, 2021). Therefore, an adequate supply of K is required for high biomass production, leaf development and overall tuber yield (Abd El-Latif *et al*., 2011; Panthi *et al*., 2019; Koch *et al*., 2020).

2.4. Effect of mulch on the growth and yield of potato

Mulching is an effective method for modifying plant microenvironment to increase crop yield (Li *et al.* 2018b). Mulching covers the soil surface and thus helps maintain soil temperature which has a positive effect on overall crop growth (Iqbal *et al.* 2020). High-temperature delays or prevents tuber formation in most cases, with tuber formation rarely occurring above 30°C (Waheed *et al*., 2023). By covering the soil surface, mulch influences the hydrothermal conditions of the soil by either increasing or decreasing the soil temperature depending on the type of mulch (organic, inorganic and mixed mulching), which can reduce soil water evaporation under reduced soil temperatures (Sinkevičienė *et al*., 2009; Dvořák *et al*., 2012; Li *et al*., 2018b; Alicia *et al*., 2021).

Increased soil water retention through mulching could also help increase nutrient availability and nutrient uptake by plant roots (Atmai, 2022). Through moderating soil temperature fluctuations, mulch can reduce the rate of nitrogen volatilization by keeping the soil cooler, especially during hot periods. High soil pH and high temperatures cause higher volatilization rates because they increase soil concentrations of ammonia dissolved in soil water and warm soil water cannot hold as much ammonia gas (Jones *et al*., 2013; Guo *et al*., 2019; Zhenghu and Honglang, 2000). In general, nitrogen volatilization becomes more significant as soil temperatures rise above 10 to 15°C and can become even more pronounced at temperatures above 21°C (Jones *et al*., 2013).

Organic mulch not only helps reduce nitrogen volatilization, but also contributes to nutrient availability in the soil through the process of decomposition (Sinkevičienė *et al*., 2009; Du *et al*., 2022). As organic mulch breaks down, it undergoes microbial and chemical processes that release nutrients slowly and steadily into the soil over time (Jodaugienė *et al*., 2010; Qu *et al*., 2019; Majumdar *et al*., 2022). The positive influence of mulch on the plant microenvironment can, therefore, play a critical role in improving NUE, plant growth, yield and yield quality of potatoes (Ahmed *et al*., 2017; Li *et al.*, 2018b; Wang *et al*., 2019b).

2.5. Effect of cultivar selection on growth and yield of potato

Cultivar selection plays a significant role in determining the growth and yield of potato plants. The impact of cultivar selection on growth and yield includes factors such as disease resistance, environmental adaptability, tuber quality, and overall productivity (Likhnenko *et al.* 2020; Tessema *et al*., 2020; Mthembu *et al.,* 2022). Potato cultivars are classified into maturity groups (early, medium, and late cultivar) according to the length of the vegetation period required to produce a harvestable product (Plich, 2017; Nasir and Toth, 2022). The duration of the growing period influences how long the plant has to capture sunlight, convert it into energy through photosynthesis, and allocate resources to tuber growth consequently influencing the overall tuber yield (Oliveira *et al*., 2016).

Early maturing cultivars have a shorter growing period, which means their vegetative growth phase (canopy development) is compressed into a shorter timeframe (Getahun *et al*., 2020). They have a reduced period for photosynthesis, nutrient uptake, and overall plant development. As a result, early maturing cultivars tend to have smaller above-ground plant structures with less foliage and thinner stems due to limited duration of active leaf growth, which is a major yield limiting factor in early maturing cultivars (Wadas and Dziugiel, 2013). This leads to lower biomass accumulation compared to late maturing cultivars. This can result in smaller tuber sizes and lower total tuber yield per plant compared to later-maturing cultivars (Tekalign and Hammes, 2005; Tsegayo *et al*., 2018).

Late maturing potato cultivars have a longer growing season, allowing them to accumulate more biomass over a prolonged period (Nasir and Toth, 2022). This extended growth period allows for increased photosynthesis and nutrient uptake, leading to greater plant development and overall biomass production (Tekalign and Hammes, 2005; Haverkort and Struik, 2015). As a result, late maturing cultivars often have larger above-ground plant structures, including more extensive foliage and thicker stems (Hill *et al*., 2021). This often leads to larger tuber sizes and potentially higher total tuber yield per plant. The greater the above-ground biomass (particularly the healthy leaves), the more photosynthates are available to be transported and accumulated in the tubers, contributing to higher tuber yield (Oliveira, 2000). Most potato cultivars have a shallow root system, but the root length varies among the cultivars (Nasir and Toth, 2022). However, this varies depending on the cultivar; for example, some varieties with wider and longer root systems have a higher probability of being able to extract water and nutrients from the soil, increasing overall tuber production (Zarzyńska *et al*., 2017).

2.6 Response of potato crop to integrated inorganic fertilizer, mulch, and cultivar selection

No single source of plant nutrients, such as chemical fertilizers, organic manures, crop residues, and bio-fertilizers, can meet the entire nutrients need of a crop in today's intensive agriculture systems (Paramesh *et al*., 2023). The combined application of inorganic fertilizer and organic material, usually termed integrated nutrient management, is widely recognized as a way of increasing yield and/or improving productivity of the soil sustainably (Biramo, 2018). Considerable improvement in quantity and quality of exhaustive and responsive crop like potato has been observed under integrated use of organic and inorganic fertilizers as compared to recommended dose of nutrients applied with inorganic fertilizers alone (Ferdoushi *et al*., 2010; Bayu *et al*., 2006; Asfaw, 2016; Pandit *et al*., 2018; Wagari *et al*., 2022). More or less the same economic yield could be obtained by the integrated use of half or reduction of the recommended dose of fertilizers along with organic manures which can save approximately 50% of the inorganic fertilizers (Kumar and Shivay, 2010; Kumar *et al*., 2012; Rajiv, 2014; Chaudhary and Rawat, 2022).

Incorporating cultivar selection into the broader context of INM demonstrates the holistic nature of sustainable agriculture. Different cultivars have varying nutrient requirements based on their genetics and growth patterns (Maltas *et al.*, 2018; Muleta and Aga, 2019). Some cultivars might be more efficient in nutrient uptake and utilization, making them better suited for INM systems where nutrient availability is carefully managed. However, most fertilizer recommendations do not take into account differences in nutrient use efficiency between cultivars. Newly released potato cultivars such as Sababa, Tyson, and Panamera require additional revision to develop the best management recommendations for N fertilization of potatoes and for optimizing tuber yield and quality (Muleta and Aga, 2019).

2.7. Response of soil quality to integrated inorganic fertilizer, mulch, and cultivar selection

Integrated use of all sources of plant nutrients is important not only for increasing crop productivity but also for improving soil health essential for sustaining the crop productivity in a long term and on the other side, a judicious combination of organic and inorganic sources of nutrient might be helpful to obtain a good economic return with strong soil health (Figure 2.2) (Hensh *et al*., 2020). Incorporation of organic materials either in the form of crop residue, organic manure or amendment has a significant effect on SOM (Ning *et al*., 2017; Li *et al*., 2021). Among the benefits of maintaining or increasing SOM through organic materials are increased soil water-holding capacity, improved soil structure for root growth and drainage through improving aggregate stability and decreasing soil bulk density, accelerated rates of nutrient cycling and higher content of soil nutrients over a longer period of time, increased CEC, and greater soil biological activity (Garcia-Gil *et al*., 2000; Asfaw, 2016; Ning *et al*., 2017; Abid *et al*., 2020; Nakade *et al*., 2021). The use of organic and chemical fertilizers ensures a continuous supply of nutrients, acting as a multi-nutrient pool and gradually releasing nutrients during organic matter mineralization. (Abid *et al*., 2020; Ejigu *et al*., 2021; Paramesh *et al*., 2023).

It has been found that organic mulch increases soil moisture through improved infiltration whereby mulch materials immediately break the speed of water in hilly areas and increase the infiltration rate of soil and also through reduced evaporation, or better moisture conservation (Chaudhry *et al*., 2004; Mkhabela *et al*., 2019; Iqbal *et al.*, 2020; Waheed *et al*., 2023). Furthermore, these actions tend to reduce soil and water loss that occur through erosion and runoff in arable lands (Chaudhry *et al*., 2004; Prosdocimi *et al*., 2016; Abrantes *et al*., 2018). Therefore, an integrated nutrient management approach that acknowledges the need for both organic and inorganic mineral inputs is promoted due to positive interactions and complementarities between them (Abedi *et al*. 2010). Thus, adopting this strategy should increase crop productivity, prevent soil degradation, enhance carbon storage in the soil and also reduce emissions from nitrogen fertilizer use and thereby help meet future food supply needs (Demelash *et al.*, 2014). Despite the stated benefits of INM, majority of INM research focuses on organic materials as a means of increasing soil nutrient content rather than increasing nutrient content and minimizing nutrient and water losses due to evaporation and volatilization, respectively, especially in warmer regions of Africa. The INM practice must also promote methods such as soil cover in form of organic mulching designed to reduce nutrient losses and enhance plant nutrient uptake (Zhang *et al*., 2012).

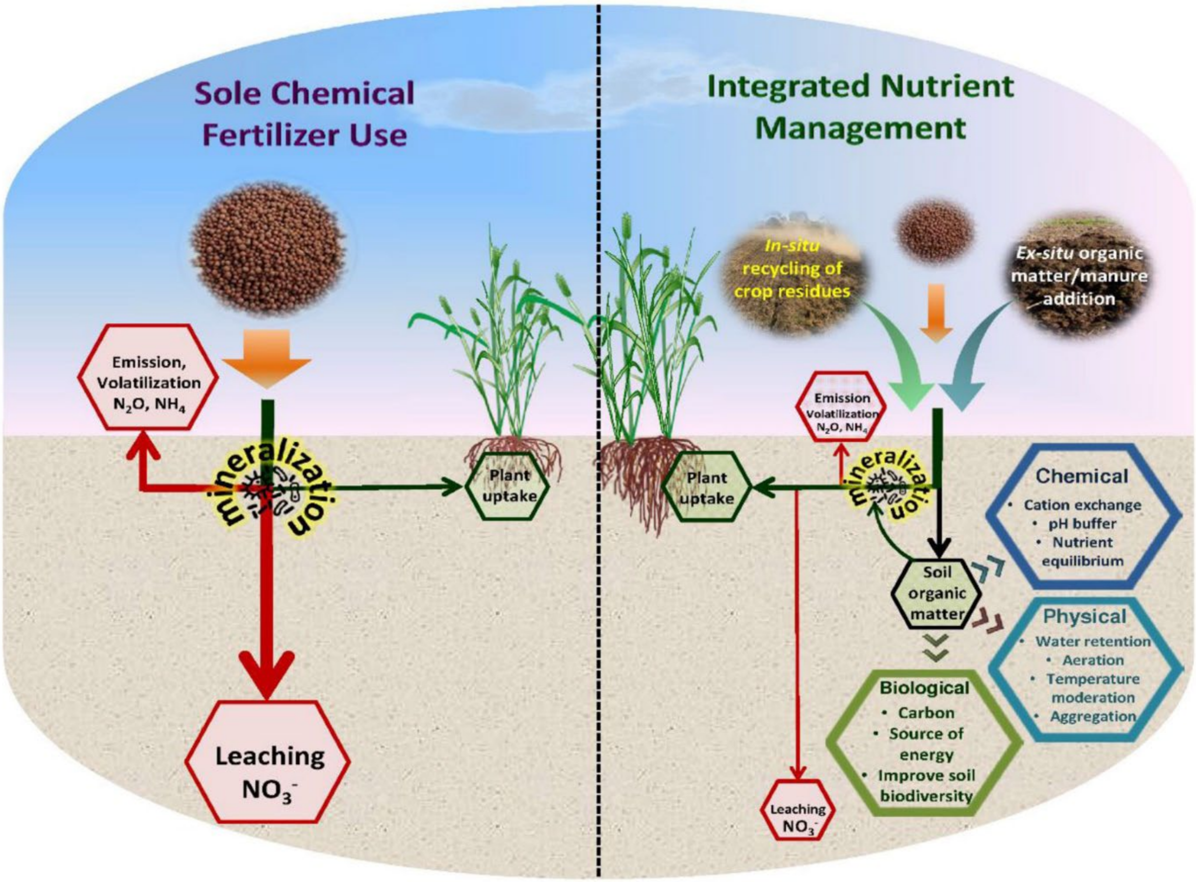

Figure 2.2: Influences of sole chemical fertilizer vs. integrated nutrient management on the nitrogen pools, mineralization, leaching, and volatilization fluxes (Bhardwaj *et al*., 2023).

2.8. Conclusion and Recommendations

The aim of this review was to give an account of integrated nutrient management to optimize potato growth and tuber yield and to improve productivity of soil physicochemical properties. Africa's potato yields are generally unsustainable and fluctuate greatly as a result of issues with soil nutrients. In this instance, it is evident that excessive application of inorganic fertilizers, particularly N, poor selection of cultivars, uneven distribution of rainfall, high temperatures, and sandy soils considerably lower soil quality, which in turn reduces potato yield and quality. Potato yields are reduced as nutrient uptake is hampered by nutrient losses due to increasing use of inorganic fertilizers, shallow potato roots, leaching and volatilization. INM can maximize potato yield, tuber quality, and limiting nutrient losses without degrading the quality of the soil, thus a likely candidate strategy for lowering excessive use of inorganic fertilizers in potato production. Experiments have shown that the combination of inorganic and organic fertilizers can achieve almost the same economic yield by reducing the amount of inorganic fertilizer applied. Judicious use of N, P and K plays a crucial role in promoting plant growth and increasing potato yield. Soil cover through mulching moderates soil temperatures and reduces nutrient losses. However, instead of using organic mulch as a tactic to reduce nutrient losses brought on by volatilization, several INM research employs mulch primarily as a source of nutrients. Future suggestions call for using organic mulch to improve soil quality and potato yield in INM by increasing nutrient content and decreasing nutrient losses. Moreover, a large number of other INM studies do not examine the differences in nutrient requirements across cultivars, indicating that future research can refocus on integrating nutrient-efficient cultivars in INM systems to maximize production with the least amount of adverse environmental effects.

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CHAPTER 3: POTATO GROWTH AND YIELD RESPONSE TO INTEGRATED NUTRIENT MANAGEMENT CENTRED ON FERTILIZER APPLICATION, SOIL COVER AND CULTIVAR SELECTION

ABSTRACT

The productivity of potatoes in Limpopo province is limited by poor soil fertility, which is caused by soil degradation, poor fertilizer application and management, and high temperatures that increase soil evaporation and volatilization. Therefore, the study was conducted to evaluate the potential of integrating cultivar selection, soil cover and judicious nutrient application to reduce soil fertility-based potato yield gap. The field trial was laid out as split-split plot in a randomized complete block design with three fertilizer application rates (0%, 50%, and 100% of the recommended fertilizer application rates from soil test), two soil cover levels (lucerne grass mulch and no mulch) and four potato cultivars (Mondial, Sababa, Panamara, and Tyson) replicated three times. Crop data collection included phenological development, canopy cover, biomass accumulation and yield. Panamera yielded significantly higher tuber yield (41.29 t/ha) when planted under reduced fertilizer application rates and mulched soil conditions. Significantly lower canopy cover (60.42%) and number of tubers (5.83/ plant) were obtained from the control treatment (0% fertilizer application rate without soil cover). The integration of mulch application with Panamera and Mondial showed superior shoot dry biomass (5 t/ha) when compared to other secondary interactions. Panamera outperformed other cultivars with respect to phenological progression, shoot and root dry biomass and yield components. Application of 100% fertilizer recommended rate on potato fields resulted in significantly high canopy cover, shoot dry biomass and tuber fresh mass. Mulch application tended to significantly increase time to maturity, maximum canopy cover, biomass accumulation and total tuber yield. The high tuber yield of Panamera was attributed to the extended period of biomass accumulation and partitioning in potato plants. Improved growth and yield components in potato fields covered with mulch were associated with decreased soil moisture and nutrient loss. N, P and K indicated to play a vital role required for the proper functioning of plants metabolic processes for optimal growth and yield of potatoes. Therefore, farmers can look into integrating cultivar

Panamera, 50% recommended fertilizer rate and mulching to produce sustainable potato yields.

Keywords: growth, fertilizer application rates, mulch, soil fertility, potato cultivar, yield

3.1 Introduction

Potato (*Solanum tuberosum* L.) plays a crucial role in ensuring food security and increasing farmer income due to its high yield potential in many parts of Africa (Van der Waals and Krüger, 2020; Xu *et al*., 2022). Among food crops in terms of consumption, potato ranks fourth after maize, wheat and rice (Ahmadu *et al.,* 2021). Potato yields in South Africa (SA) are approximately 36.2 t/ha and a large portion of this yield (approximately 22%) is produced in Limpopo province (Koch *et al*., 2020; Vosloo, 2021). Despite its high contribution, potato production in the province faces various challenges that can potentially reduce yields. These challenges include climate (drought and high temperature), use of low-quality seed potatoes, low-yielding cultivars, poor disease management, and inadequate soil fertility management (Muthoni and Shimelis, 2020; Shimira *et al*., 2020; Tunio *et al*., 2020).

The downward spiral of soil fertility has led to a corresponding decline in crop yields, food insecurity, and environmental degradation due to inappropriate soil fertility management practices (Mafongoya *et al*., 2006; Lan, 2015). Most farmers, particularly smallholder farmers, rarely apply fertilizers at the recommended rates and at the appropriate time because of the high cost of fertilizers and poor soil fertility testing (Mafongoya *et al*., 2006). Many productive soils have been chemically, physically, and biologically degraded due to inappropriate use of synthetic fertilizers (Krasilnikov *et al.,* 2022). Continuous inadequate use of chemical fertilizers decreases the nutritional quality of crops (Krasilnikov *et al*., 2022). In Limpopo, this is further exacerbated by the prevalence of extreme weather conditions such as drought, high temperatures, and erratic precipitation, which increase nutrient losses from the soil through increases in evaporation and nutrient volatilization (Kome *et al*., 2018; Dari *et al*., 2019; Nyawade *et al.,* 2021; Elbasiouny *et al*., 2022). Furthermore, Limpopo is characterized by sandy soils with low cation exchange capacity (CEC) and low water holding capacity (WHC) which increases nutrient losses through leaching (Ramakadi, 2021; Mokgolo and Mzezewa, 2023; Swafo and Dlamini, 2023). Most farmers inadequately apply nutrients and use uncertified seed, which further increases the nutrition-based yield gap (Nabel *et al*., 2016).

Potato cultivars differ in various nutrition enhancing characteristics such as rooting depth, potential yield, crop canopy, harvest index, and time to maturity. These characteristics can be exploited to reduce nutrient losses, improve nutrient uptake, and improve potato yields under soil nutrient-limiting conditions (Hernandes, 2011; Kolech *et al*., 2015; Howlader *et al*., 2017). Late-maturing cultivars typically have a longer growing season, and therefore have a longer period to take up nutrients from the soil (Makani *et al*., 2020). The high canopy cover tendency of late-maturing cultivars reduces climate-induced nutrient losses by shading the ground and lowering soil temperature, thereby reducing evaporation and volatilization (Wang and Liu, 2007; Jones *et al.,* 2013; Getahun *et al*., 2020). However, the growing pattern of late-maturing cultivars may require more nutrients, particularly nitrogen, to support the plant's growth and development throughout the season. In contrast, early maturing cultivars typically have a shorter growing season, and therefore may have a shallower root system and a smaller canopy cover (Hill *et al*., 2021). As a result, they may require less fertilizer to support their growth and development, although this may occur at the expense of tuber yield. A shorter growing season of early maturing cultivars results in excess nutrients remaining in the soil and at risk of volatilization and leaching. These various morphological and developmental characteristics of potato cultivars largely influence the growing pattern, intercultural operations (fertilizer application and mulching) or yield of a particular cultivar (Howlader *et al.*, 2017).

The continued lack of required nutrient replenishment of nutrient-depleted soils as well as climate-induced nutrient losses are not only exacerbating soil degradation, but also jeopardizing agricultural sustainability in many parts of Africa (Bouwman and Boumans, 2002; Tan *et al*., 2015). This is because potato is a heavy feeder crop requiring large quantities of nutrients to produce high tuber yield (Atanaw and Zewide, 2021). Potato plants require a variety of elements for growth and development, of which N, P and K are the most important and play a critical role in the yield and quality of tubers (Koroto and Dula, 2019; Bhujel *et al*., 2021). Strategies to mitigate nutrient losses and poor soil fertility include not only judicious application of nutrients but also application of organic mulch. Organic mulch can aid in supplying these nutrients without increasing the already high fertilizer application rates, as it decomposes over time, releasing N, P, and K into the soil (Ramineh *et al*., 2023). Mulching reduces soil nutrient loss by regulating temperatures, reducing evaporation and volatilization without reducing crop yields, thereby achieving sustainable agriculture production levels (Kader *et al*., 2019; Shaji *et al*., 2021). It is therefore important to integrate judicious fertilizer application with organic mulch and improved cultivars to increase potato yield with minimal adverse impact on soil quality. The study was conducted to investigate the interaction effect of potato cultivar selection and grass mulch application under varying soil fertility levels on potato growth and yield under irrigated conditions.

3.2 Material and method

3.2.1 Study site description

A field trial was conducted over a single potato growing season (spring) in 2022 at the University of Limpopo Sykerfuil experimental farm (23°50’ 2.98 S; 29°41’31.11 E), at an elevation of 1242 m, near Polokwane in the Limpopo Province of South Africa. The region receives mean annual precipitations of about 405 to 500 mm occurring mostly in the summer months of October to March. The temperature in winter ranges between 5 and 28°C and in summer temperature ranges from 10 to 36 °C (Tyasi *et al*., 2022). The minimum and maximum temperature readings were recorded from the weather station at the farm throughout the growing season (Figure 3.1). The region received severe hail 49 days after planting (DAP), which caused severe damage on the canopy of the planted crop.

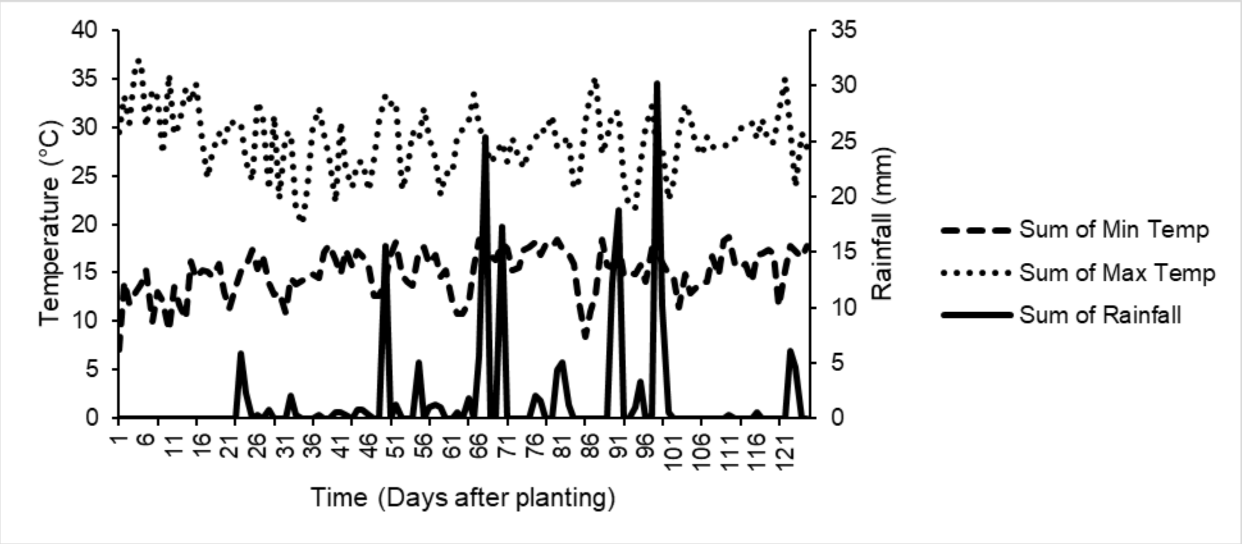

Figure 3.1: Minimum, maximum temperatures, and rainfall of the study site recorded throughout the growing season at the University of Limpopo Sykerfuil experimental farm.

3.2.2 Soil classification and analysis prior to experimentation

A 1 m soil profile pit was dug on the experimental unit for soil classification and sampling. A Taxonomic System for South Africa (Memoirs on the Agricultural Natural Resources of South Africa No. 15) and HM-519 Munsell soil colour books were used for classification of the experimental area where the representative profile pit was dug. Three different soil horizons were identified by using the soil colour across the profile and the hand feel method to determine the change in soil texture between the horizons. A measuring tape was used to measure the depth of the horizons and the total depth of the soil profile. Three samples were collected from the Orthic A and Red apedal B horizons using a bulk density core, steel cylinder, and hammer to determine the bulk density. Three more soil samples were collected from the same horizons using a spade for soil textural class (sand, clay, and silt) analysis. Prior to planting, soil samples were collected using a grid sampling method whereby small samples were taken at an equal distance across the experimental plot with a soil auger. Eighteen soil samples were collected from the experimental unit using the grid method. For each sampling unit, one soil sample was collected from the Orthic A and Red apedal B horizon to reflect the effective rooting depth of potatoes. The Global Positioning System (GPS) was used to determine the elevation and GPS coordinates.

Soil samples for bulk density were oven dried at 105°C for a period of three days. The dried samples were weighed using the electronic weighing balance and the volume of the core ring was calculated to determine the bulk density of the soil together with the dried soil samples. Bulk density was calculated by dividing the mass of each dried soil sample by the volume of the cylindrical core. The other collected soil samples were transported to Cedara College of Agriculture for soil physical (soil texture) and chemical (mineral nitrogen, phosphorus and potassium) analysis (Table 3.1 and 3.2 respectively). Soil textural analysis was conducted using the international pipette method. Colorime-Tric and Bray 1 methods were used to measure mineral nitrogen (NO^{3-} and NH^{4+}) and phosphorus concentrations, respectively. Soil K was quantified using the ammonium acetate extract from the cation exchange capacity determination.

Table 3.1: Table 1: Soil physical properties before planting

Soil physical properties	**Soil horizon**		
	Orthic A	**Red Aphidal B**	**Softpan apedal B**
Depth	0.3 m	0.5 m	0.2 m
Texture	Sandy clay loam	Sandy clay	-
Bulk density	1.5	1.4	-
Soil form		Kimberley	

Table 3.2: Soil chemical properties before planting

Nutrient	Soil test (kg/ha)	Crop required (kg/ha)	Deficit (kg/ha)	100% fertilizer application (kg/ha)	50% fertilizer application (kg/ha)
N	60	240	180	240	120
P	1.6	135	133.4	133.4	66.7
K	52	130	78	78	39

3.2.3 Experimental design, procedure, and treatments

The field trial for the spring season was planted on the 29th of September 2022. The basis for choosing this planting date was on the avoidance of very high temperatures to allow tuber initiation to occur before the onset of high temperatures in summer that can hinder tuber initiation. Time of planting should be manipulated to allow tuber initiation during relatively cool periods. High air and soil temperatures during November and December make these two months a poor planting time in most potato-producing areas (FSSA, 2000). The experiment was laid out as a split-split plot in a randomized complete block design (RCBD) with three replications. Compound fertilizer application levels (control, 50%, and 100% fertilizer application) were the main blocking factor. The control block was the plot where no fertilizer was applied. The crop response in the control plots demonstrated and measured the nutrients supplied by the soil. The fertilizer application rate of nitrogen (N), potassium (K) and phosphorus (P) was calculated using the N, P, and K recommended application to obtain the yield target of 60 t/ha based on the study site soil physicochemical analysis results from Cedara College of Agriculture. The principle is to establish the yield potential first and then calculate the required fertilizer rate (FSSA, 2000). Therefore, the fertilizer application of 240, 135, and 108 kg/ha of N, P, and K, respectively, represented the 100% fertilizer application level. The 50% fertilizer application block represented the block in which half of the total 100% NPK application was applied. This resulted in a 50% fertilizer application level consisting of 120, 67.5, and 54 kg/ha of N, P, and K, respectively. The P:K ratio was used to select a fertilizer containing an NPK ratio of 2:3:2 (22) + Zn.

Balance for P procedure was used to determine the amount of fertilizer mixture to apply to reach the yield target. The concentration of each nutrient in the fertilizer mixture was determined as follows:

$$\text{Ratio of the nutrient per 100 kg} = \frac{\text{Individual ratio of the nutrient}}{\text{sum of ratios}} \times mass\ of\ NPK\ in\ 100\ kg$$

Balance for P was conducted as follows:

$$\text{Amount of fertilizer mixture} = \frac{\text{Recommended P dose}}{\text{Ratio of P per 100 kg}}$$

The amount of N, P, and K in the fertilizer mixture can be excess or deficit depending on the recommended application rates. To determine the amount of N, P, and K in the fertilizer mixture the following formula was used:

Amount of nutrient = Amount of fertilizer mixture × Ratio of the nutrient per 100 kg

To address a nitrogen deficit in the calculated fertilizer mixture, urea (46% N) was added alongside NPK compound fertilizer to achieve the desired yield.

$$\text{Amount of Urea to supply the deficit N} = \frac{\text{Deficit N}}{\text{46 kg N}} \times 100\ kg\ fertilizer$$

Each block was 27 m long and 13.8 m wide, and these three (3) main fertilizers levels blocks were separated by a 10 m pathway distance to limit the lateral flow of nutrients between the blocks. This resulted in a total experimental area of 1 393.8 m^2 (13.8 m × 101 m). Mulch application (no mulch and 100% grass mulch) was the main sub-blocking factor. The no-mulch application sub-block represented the plot whereby the soil was left uncovered. The 100% grass mulch sub-block represented the plot that is totally covered by lucerne grass mulch. Lucerne grass mulch was spread evenly to cover the entire plot area in mulch treatment plots at 6000 kg/ha when 90% of potato seedlings had emerged (approximately 25 - 30 days after planting). The sub-blocks were separated by a 5 m pathway to limit the accumulation of mulch on non-mulched plots.

Each sub-block consisted of four (4) potato cultivars (Mondial, Sababa, Panamera, and Tyson) which served as a third experimental factor. Potato seeds were obtained from Wesgrow®, a seed company that supported this study. The selected potato cultivars differ in growing seasonal length, canopy characteristics, disease tolerance, and potential tuber yields. Mondial is a drought tolerant, high-yielding cultivar that takes 90-110 days to maturity. Tyson is a medium late cultivar (90-110 days to maturity) and was bred to maximize yields under climatic conditions similar to those of the Limpopo province. Panamera is a late-maturing cultivar (110-150 days), while Sababa is a high-yielding, early-maturity (less than 90 days to maturity), newly introduced cultivar. Agronomic information is well-documented for Mondial, while it is not well-documented for the other three cultivars that were used in this study (Nkhase, 2019; Mthembu *et al.,* 2022). A 1 m distance was used to separate the planted potato cultivars. This resulted in a 3×2×4 factorial treatment structure with 72 experimental units. Each plot was 3 m long and 2.7 m wide, with intra-row spacing of 0.3 m and inter-row spacing of 0.9 m.

3.2.4 Land preparation and management practices

Mechanical land preparation was conducted using mouldboard-plough and disc plough to loosen the soil. Plot demarcations in individual plots were done manually using strings, markers, hoes, and a 100 m measuring tape. Medium and well-sprouted tubers were used for planting. The seeds were planted directly into the soil surface using hand hoes at a planting depth of 10 cm. After planting, two 1 m access tubes per sub-plot were carefully installed into the soil to determine the amount of moisture in the soil during the growing season using the PR 2/4 soil moisture probe. A calibrated HH2 moisture meter (Delta-T Devices Ltd, England) was used to readout and store the corresponding soil moisture content from the probe. Irrigation to 100% field capacity based on the measured soil moisture content, was applied using a sprinkler irrigation system. Irrigation was withdrawn 85 days after planting due to frequent rainfall.

Manual weeding, using hand hoes was conducted to keep the experimental units weed-free throughout the potato growing season. Ridging was conducted after crop emergence using hand hoes to enhance stolon development, kill weeds, prevent tubers greening and facilitate harvesting. Potato plants mainly rely on the seed tubers for nutrients up to tuber initiation, where an additional supply of nitrogen before tuber initiation can suppress tuberization (Zebarth and Rosen, 2007). As a result, the first half of the split fertilizer application was applied soon after tuber initiation (45 DAP) to avoid suppressing tuberization. Potato nitrogen and potassium uptake is highest during the tuber bulking stage (Horneck and Rosen, 2008; Koch *et al.,* 2020). Therefore, the second half of the split fertilizer application was applied during the tuber bulking stage (75 DAP) using the banding application method to optimise tuber bulking. Efekto Malasol (Agro-Serve (Pty) Ltd) pesticide was applied at 93 DAP to control Aphids. Bird damage caused by Guinea fowls at emergence, was controlled by establishing scarecrows across the experimental units.

3.2.5 Data collection

3.2.5.1 Phenological development

Phenological stages were recorded on the experimental rows from emergence to senescence. Days to emergence were recorded when 90% of the plants had emerged above the soil surface, days to flowering were recorded when 50% of the plants in the experimental row extruded flowers, days to the end of flowering were recorded when 50% of the plant's flowers on the experimental rows curled in and fell off. The duration of flowering was then calculated as the difference between the days taken to 50% flowering and days to end flowering. Days to reach maximum canopy cover were recorded when 50% of the plants on the experimental row reached the highest canopy, and days to canopy cover decline were recorded when the canopy dropped. The duration of maximum canopy cover was then calculated as the difference between days to reach maximum canopy cover and days to maximum canopy decline. Days to physiological maturity were recorded when 90% of plants per treatment were ready for harvest, as shown by the senescence of the haulms on the experimental rows.

3.2.5.2 Crop growth

An automatic colour threshold (ACT) image analysis tool called Canopeo (Mathworks, Inc., Natick, MA) was used to measure the fractional green canopy cover weekly from the seventh week after sowing to harvest maturity. Fractional green canopy cover (FGCC) estimates crop canopy development (Patrignani and Ochsner, 2015). Downward-facing images were taken from three (3) randomly selected plants per treatment using a smartphone camera. To minimise overestimation of FGCC, the camera was kept at about 0.5 m distance from the top of the canopy.

3.2.5.3 Biomass accumulation and tuber yields

Destructive growth harvest was conducted at physiological maturity to determine the biomass accumulation and tuber yield. One plant per treatment was randomly selected from the experimental rows and harvested with the use of a spading fork, and a scissor was used to separate the plant into roots, shoots, and tubers. The samples were washed with tap water to remove soil and other foreign materials. Fresh roots and shoots were oven-dried at 65°C for 48 hours to determine the dry biomass using an electronic weighing balance. Number of tubers per plant and average tuber mass are key components of estimating potato yields (De la Morena *et al*., 1994). For this reason, the number of tubers per plant was physically counted on the harvested plants per treatment and fresh tuber yield was determined by weighing the tubers and expressing the values in t/ha.

3.2.6 Data analysis

All the collected data were subjected to analysis of variance (ANOVA) using GenStat® version 21 (VSN, International, United Kingdom). Means were separated using the least significant differences (LSD) at a probability level of 95% and multiple mean comparisons were conducted using the Bonferroni test.

3.3 Results and Discussion

3.3.1 Phenological development

Primary integration (F x C x M) had no significant influence on potato phenological development. However, a secondary integration (F x M) indicated a significant influence on time to flowering, which was due to the high significant influence of fertilizer application rates on time to flowering, rather than mulch application, which had no significant influence on the time to flowering. The selected cultivars differed significantly in all the measured phenological development stages. The application of mulch had a highly significant impact on time to maturity. It was expected that mulch application and fertilizer application rates would not have a significant impact on the time to emergence as these treatments were applied after full emergence.

Table 3.3: Summary of p values from the ANOVA indicating the effect of integrating fertilizer application rates, mulch application, and different potato cultivars on potato phenological development.

Source of variance	**P-values**			
	TtE	**TtF**	**DoF**	**TtPM**
Fertilizer application rate (F)	-	**<0.001**	0.376	0.085
Cultivar (C)	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Mulch (M)	-	0.144	0.323	**<0.001**
F x C	-	0.133	0.437	0.868
F x M	-	**0.030**	0.376	0.728
C x M	-	0.387	0.401	0.207
F x C x M	-	0.804	0.437	0.338

Note: TtE= time to emergence, Ttf= time to flowering, DoF= duration of flowering, TtPM= time to physiological maturity.

3.3.1.1 Fertility-induced reduction in time to flowering

The interaction of increasing fertilizer application rates and applying mulch on potato fields significantly decreased time to flowering (Figure 3.2A). The observed differences were driven by highly significant reductions in time to flowering when fertilizer application rates were employed (Figure 3.2B), rather than application of mulch which did not result in any statistically significant alterations in time to flowering. Lack of fertilizer application in the control plots increased time to flowering by approximately 4 days relative to the full fertilizer application rate. The observed results are contrary to expected outcomes where nutrient deficiency generally hastens potato phenological development and time to flowering (Cho *et al*., 2017; Gelaye *et al*., 2022). Phosphorus deficiency tends to induce escape mechanisms where sex hormone signals are produced to hasten flowering for the crop to mature early (Gelaye *et al*., 2022). Similarly, nitrogen deficiency promotes transition from vegetative to reproductive stage, resulting in early flower development under N stress (Lin and Tsay, 2017; Godebo *et al*., 2020). The crop was hit by hail and post recovery to hail in the plot where fertilizer was not applied was low. Hail damage can stress the plants, leading to a temporary setback in their growth whereby they prioritize recovery and survival over reproductive activities like flowering (Bal *et al*., 2014; Petoumenou *et al*., 2019). This led to an observed delay in flowering when no fertilizer was applied.

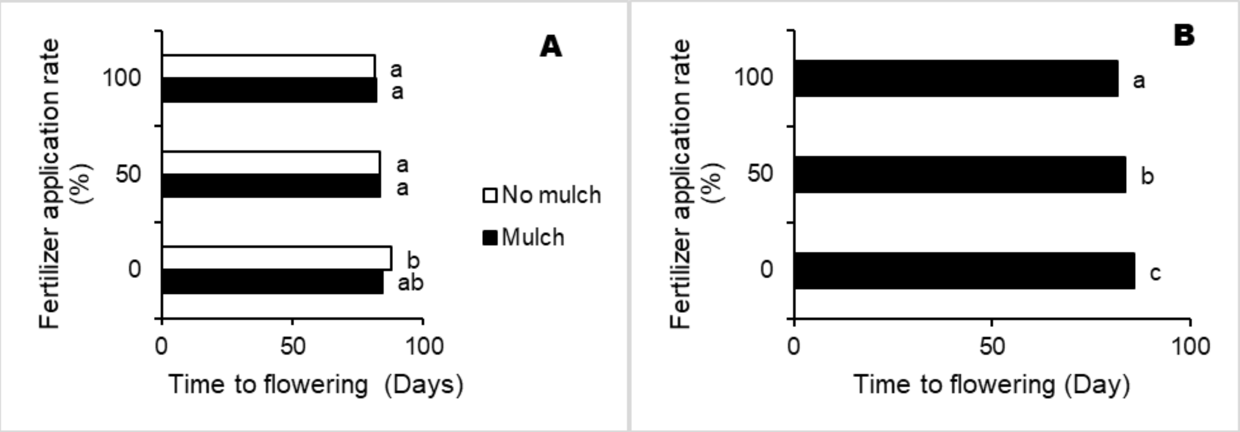

Figure 3.2: Time taken to reach flowering as influenced by the integration of grass mulch application and different fertilizer application rates (A) and various fertilizer applications rates (B) under irrigated conditions. Treatments with the same letter are not significantly different at p≤0.05.

3.3.1.2 Cultivar differences in time to phenological development

Crops undergo progressive growth stages from emergence to senescence, characterized by their reproductive capacity and phenology (Khan *et al*., 2013). Time to emergence, flowering, physiological maturity, and duration of flowering differed significantly between potato cultivars during the growing season (Figure 3.3 A, B, C and D, respectively). Potato phenological development is known to be determined by endogenous genetic components (Vreugdenhil, 2007; Cho *et al*., 2017; Getie *et al.*, 2018; Asnake *et al*., 2023), which explains the highly significant differences in phenological development observed in this study. Time taken to reach full emergence for Panamera was longer by 22 days relative to Sababa. This can be explained by the fact that this cultivar is a late maturing cultivar, making it have a higher likelihood of reaching full emergence later in the growing season than early and medium maturing cultivars. The time to physiological maturity observed in this study is related to the time taken to the full emergence of the cultivars. Panamera extended its time taken to reach physiological maturity by 11 days relative to an early maturing cultivar Sababa. The observed results for Sababa are contrary to expected outcomes where early maturing cultivars generally require a growing length of 100-110 days. Panamera shortened the time required to reach the flowering stage by 6-7 days compared to the other cultivars. The observed early flowering in Panamera may be facilitated by its high and early accumulation of canopy cover (Nyende *et al*., 2005). This is contrary to the findings by Getie *et al.* (2018), which showed that late-maturing cultivars require more days to reach 50% flowering when compared to early-maturing cultivars. Not only did Panamera reach flowering faster, but it also took longer to complete this phenological stage, resulting in a significantly longer duration of flowering. This can be attributed to its prolonged active leaf duration due to extended growing period.

3.3.1.3 Soil cover induced extension in time taken to physiological maturity

Time to physiological maturity differed significantly with respect to mulched and non-mulched potato fields (Figure 3.4). Potato fields that were left uncovered reduced the time taken to reach physiological maturity of the crops by 4 days relative to fields covered with grass mulch. Soils exposed to direct sunlight under treatments without soil cover, increase soil temperature and result in moisture and nutrient losses or stress through evaporation and volatilization (Zhou *et al.,* 2018; El-Beltagi *et al*., 2022; Zhang *et al*., 2023). Plants growing under such stressful conditions can accelerate maturation by triggering early senescence of the plant, although this may come at the cost of reduced tuber yield and quality.

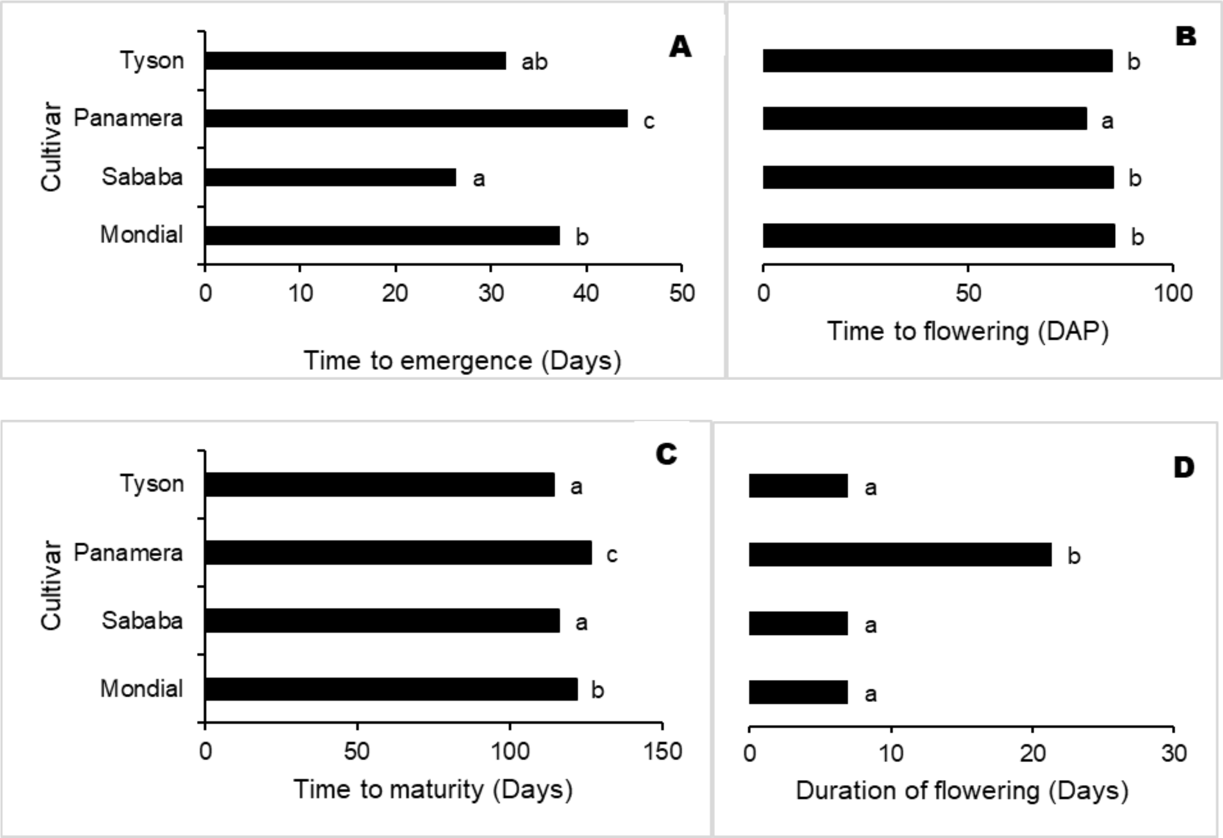

Figure 3.3: Influence of genetic difference between potato cultivars on time taken to reach emergence (A), flowering (B) and maturity (C) stage and the duration of flowering stage (D) under irrigated conditions. Treatments with the same letter are not significantly different at p≤0.05.

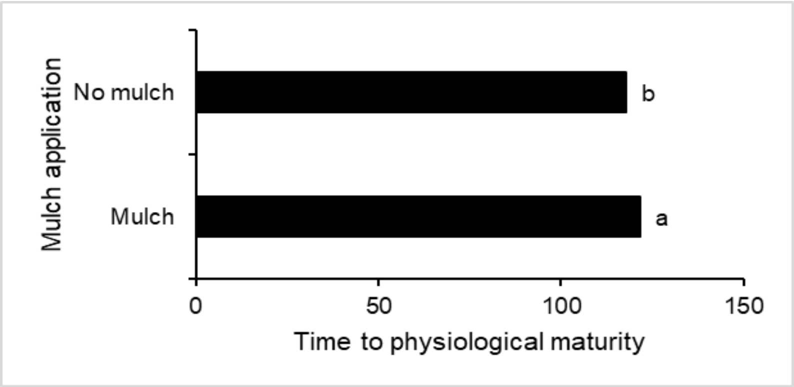

Figure 3.4: Influence of covering the soil surface with grass mulch on the time taken to reach physiological maturity under irrigated conditions. Treatments with the same letter are not significantly different at p≤0.05.

3.3.2 Crop growth and tuber yield

Maximum canopy cover was significantly affected by the secondary integration (F x M) because of highly significant differences induced by fertilizer application rates and the selected cultivars individually. However, time taken to maximum canopy cover and its duration was not significantly affected by any of the treatments. Shoots and roots dry biomass were highly affected by the cultivars and mulch application. Additionally, as a result, the secondary integration (C x M) showed a significant effect on the shoot dry biomass. Fertilizer application rates significantly affected the shoot dry biomass. The primary integration (F x C x M) had a significant influence on tuber fresh mass. The secondary integration (F x C and F x M) showed a significant impact on the tuber fresh mass. The significant impact was based on the highly significant impact of cultivars and much application rather than fertilizer application rates. The number of tubers was significantly affected by the secondary integration (F x M), which was induced by the significant effect of mulch application on the number of tubers.

Table 3.4: Summary analysis of variance indicating the effect of integrating fertilizer application rates, mulch application, and different potato cultivars on potato canopy, biomass accumulation and tuber yield.

Source of variance	**P-values**						
	TtCx	**DoCx**	**Cx**	**SDB**	**RDB**	**TFM**	**NoT**
Fertilizer application rate (F)	0.661	0.857	**<0.001**	**<0.001**	0.187	**0.047**	0.449
Cultivar (C)	0.646	0.850	0.784	**<0.001**	**<0.001**	**<0.001**	0.097
Mulch (M)	0.668	0673	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.004**
F x C	0.964	0.533	0.305	0.174	0.376	**0.011**	0.134
F x M	0.955	0.676	**<0.001**	0.317	0.651	**0.01**	**0.034**
C x M	0818	0.496	0.120	**0.006**	0.127	0.339	0.897
F x C x M	0.209	0.773	0.975	0.479	0.955	**0.005**	0.596

Note: TtCx= time maximum canopy cover, DoCx= duration of maximum canopy cover, Cx= maximum canopy cover, SDB= shoot dry biomass, RDB= root dry biomass, TFM= tuber fresh mass, NoT= number of tubers.

3.3.2.1 Maximum canopy cover

The interaction effect of 0% fertilizer application rate and no mulching on potato fields significantly decreased the maximum canopy cover (Figure 3.5). The higher maximum canopy cover under 50 and 100% fertilizer application rates is related to increased uptake of N, P and K. The observed results are in line with the expected outcomes where generally increasing the available soil nutrients results in increased crop growth (Getahun *et al*., 2020; Kabir *et al*., 2021; Kumar *et al*., 2023). Nitrogen tends to increase the number of emerging leaves and the rate of leave expansion and consequently, the development of the plant's canopy (Koch *et al*., 2020). Similar to this, phosphorous promotes root growth (Alemayehu *et al*., 2020), which ultimately enhanced plant growth and development. In addition, the N in relation to 100% fertilizer application rate increased the period of maximum canopy cover (van Keulen *et al*., 1986) particularly for Mondial (Figure 3.6A). The observed results for canopy cover overtime are contrary to expected outcomes where early maturing cultivars generally have a rapid initial canopy development and relatively shorter duration for maximum canopy cover than late maturing cultivars (Getahun *et al.,* 2020). Potassium maintains cell growth and turgor pressure, leaf expansion, and root elongation, facilitates photosynthesis and regulation of stomatal guard cells, consequently affecting the leaf area development (Prajapati and Modi, 2012; Panthi *et al*., 2019; Torabian *et al*., 2021). The lower maximum canopy cover that was observed under 0% fertilizer application rate can be attributed to N deficiency which leads to stunted growth, reduced branching, leaf surface area, and early defoliation (Nkhase, 2019; Deepika *et al.,* 2023). Similarly, K deficiency decreases the number of leaves and leaf size due to potassium’s role in osmoregulation and cell extension (Koch *et al*., 2020). Deficiencies in 0% fertilizer application fields not only reduced the canopy cover but also delayed the time needed to reach maximum canopy cover (Figure 3.6C). This means that it may take longer for plants to reach full leaf cover and overall size when soil nutrient levels are low, either because fertilizers are not applied or because there are increased losses due to lack of soil cover (Vos, 2009). However, mulch application in potato fields where 0% fertilizer application rate was employed significantly increased the overall maximum canopy cover by 18%. The observed positive effect of mulch on the maximum canopy cover can be attributed to enhanced plant hydrothermal micro-environment which might had conserved soil moisture and reduced volatilization consequently increasing the availability and uptake of nutrients to support the plant canopy (Barakat *et al*., 2020; Bhatta *et al.*, 2020).

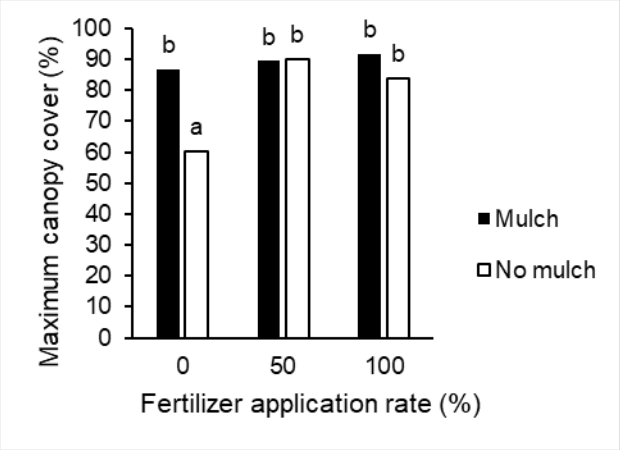

Figure 3.5: Maximum canopy cover as a function of the integration of various fertilizer application rates and mulch application under irrigated conditions. Treatments with the same letter are not significantly different at p≤0.05.

3.3.2.2 Shoot and root dry biomass

a. Fertility induced enhancement on shoot dry biomass

Dry matter partitioning to the leaves during the growing season differed significantly with respect to different fertilizer application rates (Figure 3.7). It is well known that N, P and K plays a crucial role in promoting vegetative growth, including the development of leaves and stems (Hassanzadeh et al., 2009; Godebo et al., 2020; Bhujel et al., 2021; Jiaying et al., 2022) which explain the highly significant differences in shoot dry biomass observed in this study. Across fertilizer treatments, 100% fertilizer application rate significantly increased the shoot dry biomass by 1.39 t/ha relative to 0% fertilizer application rate. High biomass under 50 and 100% fertilizer application rates is also associated with enhanced canopy cover when fertilizers are applied, which boosts photosynthetic efficiency by increasing the rate at which radiation and photons are intercepted (Koch *et al*., 2020). The amount of photosynthetically active radiation that is intercepted is a key factor in determining the potato crop's overall dry matter production and biomass accumulation, and it rises with increasing canopy cover (Nieto, 2016; Nkhase, 2019). Although fertilizer application improved the above-ground biomass, better results would have been obtained if the crop's canopy was not severely damaged by hail of which potentially negatively affected the overall yield.

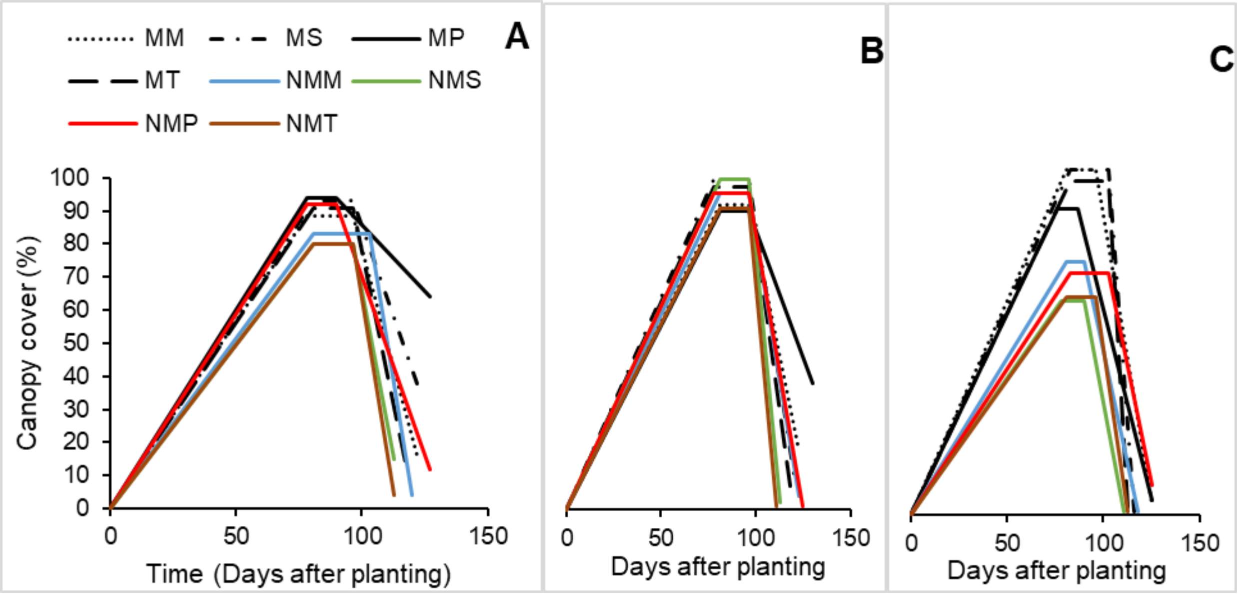

Figure 3.6: Canopy cover development overtime as influenced by the selected potato cultivars and mulch application when subjected 100, 50 and 0% fertilizer application rates (A, B and C, respectively). The figures represent time taken to reach maximum canopy cover development and its duration as a function of integrating various cultivars and mulch application with fertilizer application rates. Mondial, Sababa, Panamera, and Tyson are represented by letter M, S, P, and T respectively. Mulch and no mulch treatments are represented by M and NM respectively.

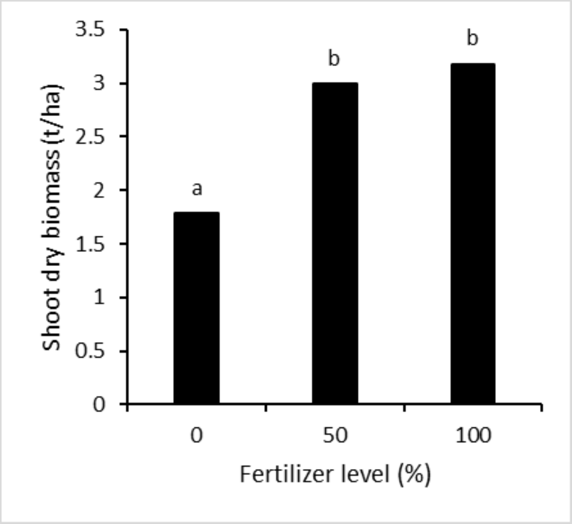

Figure 3.7: Effect of different fertilizer application rates on shoot dry biomass under irrigated conditions. Treatments with the same letter are not significantly different at p≤0.05.

b. Integration of selected cultivars and soil cover effect on shoot biomass

The application of mulch significantly increased the shoot dry biomass of Mondial by 39.80% (Figure 3.8). The interaction effect of Mondial and Panamera with mulch application seemed to significantly have a higher shoot dry biomass than other treatment combinations. Mondial and Panamera indicated to have an extended growing period (Figure 3.3C), meaning these cultivars tend to benefit more under an improved plant hydrothermal microenvironment due to mulching, hence an increase in the biomass accumulation (Kader *et al*., 2019).

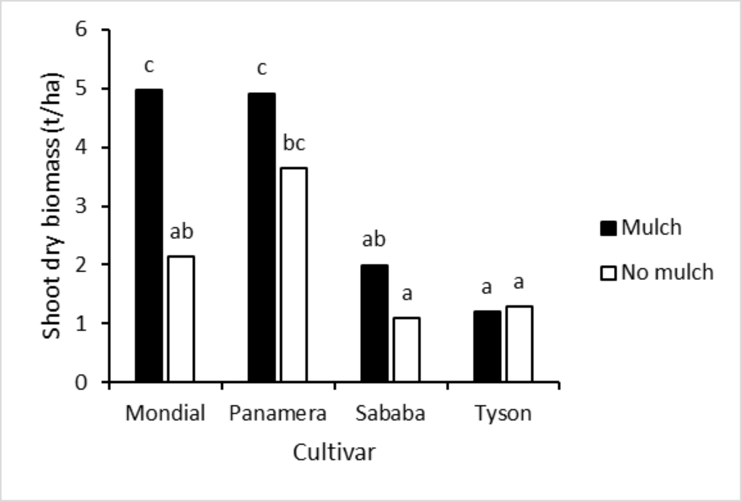

Figure 3.8: Interaction effect of various potato cultivars and mulch application on shoot dry biomass under irrigated conditions. Treatments with the same letter are not significantly different at p≤0.05.

c. Effect of mulching and cultivar differences on shoot and root biomass accumulation

The potato root system is often characterized as shallow and inefficient, with poor ability to extract water and nutrients from the soil (Joshi *et al*., 2016). In the present study, dry matter partitioning to the shoots and roots during the growing season differed significantly among the selected potato cultivars (Figure 3.9A and B respectively). This study suggests that the dry matter partitioning to leaves during the growing season differed among cultivars. This can be attributed to the difference in maturity length of the cultivars (Saluzzo *et al*., 2001; Geremew *et al*., 2007) as indicated in Figure 3.3C. Late-maturing potato cultivars such as Panamera have a longer growing season, allowing them to accumulate more shoot and root biomass over a prolonged period (Iwama, 2008). The large roots biomass Mondial and Panamera (0.28 t/ha) increases the absorption and transportation of nutrients and water to the above-ground parts of the plant, such as the shoots (Yang *et al*., 2023). This extended growth period also allows for increased photosynthesis and nutrient uptake, leading to greater plant development and overall biomass production (Raven and Edwards, 2001; Getahun *et al*., 2020). This explains the high shoot biomass of Mondial and Panamera (3.55 and 4.28 t/ha, respectively). Mulch application significantly increased shoot and root dry biomass by approximately 38% (Figure 3.9C and D respectively). These results indicated that mulching favoured better development of the shoots and roots by providing suitable moisture conditions and nutrients in the root zone (Dhakal *et al*., 2011; Bhagat *et al*., 2016; Majumder *et al*., 2016).

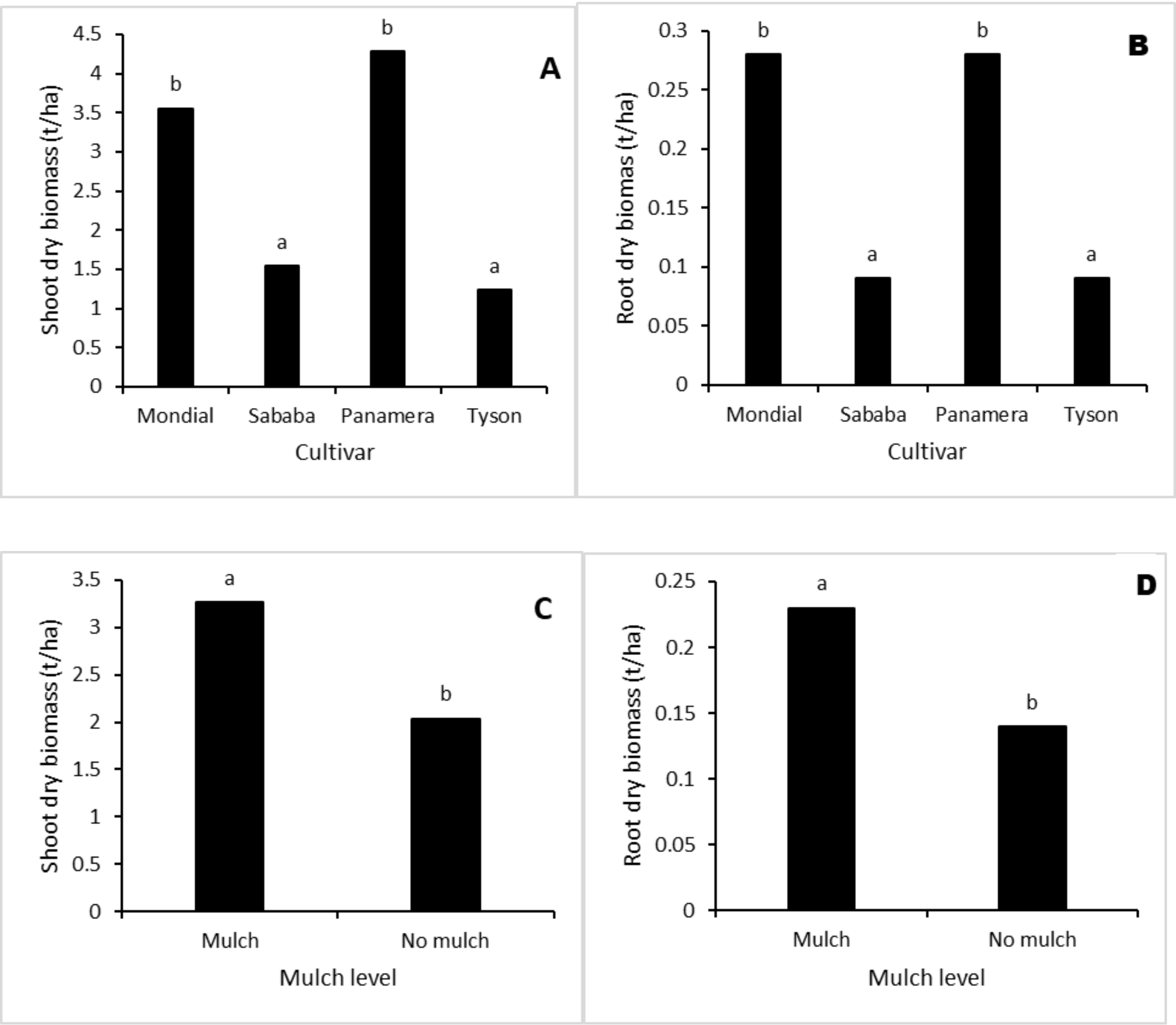

Figure 3.9: Changes in the shoot and root dry biomass as a function of various potato cultivars (A and B) and mulch application (C and D) in potato fields under irrigated conditions. Treatments with the same letter are not significantly different at p≤0.05.

3.3.2.3 Tuber fresh mass

a. Tuber yield as a function of integration of various cultivars, mulch application and various fertilizer application rates.

The yield, defined as the product of the number of tubers per plant and their mass is determined by the genotype, the environment and their interaction (Gebreselassie *et al*., 2016; Morales-Fernández *et al*., 2018). The integration of various fertilizer application rates, mulch application and various selected cultivars on potato fields significantly affected the tuber fresh mass (Figure 3.10A). The highest potato yields (49.34 t/ha) were obtained from the integration of Sababa, mulch application and 50% fertilizer application rate. The lowest (19.86 t/ha) was obtained from Tyson, no mulch and 50% fertilizer application rate.

b. Tuber yield as a function of fertilizer application and the differences in genetic composition of the selected cultivars

Tuber fresh mass is known to differ and be determined by the presence of genetic differences among potato cultivars (Getie *et al*., 2018; Merga and Dechassa, 2019; Tessema *et al*., 2020; Ngobese *et al*., 2022), which explains the highly significant differences in tuber fresh mass observed in this study. When integrated with the selected potato cultivars, various fertilizer application rates indicated to have a significant impact on tuber fresh mass (Figure 3.10B). The highest potato yields of 42.05 t/ha was produced by Panamera when full fertilizer application rate was employed. The lowest potato yields (approx. 27 t/ha) were produced by Tyson across all fertilizer levels and Mondial at 50% fertilizer application rate. Sababa was third among the cultivars to give poor tuber yields (29 t/ha) when fertilizer application rates were set to 0%. Similar high yields of Panamera were reported by Kwambai *et al*. (2023), in their study of the interactions between genotype and environment (different agro-ecologies and four consecutive seasons). However, Ngobese *et al.* (2022) reported lower yield of Panamera when compared to Mondial. The ability of Panamera to significantly accumulate greater shoot and roots biomass as indicated in Figure 3.9, contributed to translocation of assimilates to the tubers which can increase the overall yield. In addition, the greater root biomass of this cultivar enhances the plant's ability to access the applied nutrients (N, P and K) in the soil, especially during critical growth stages, and maintain optimal water uptake consequently increasing the tuber fresh mass. The increase in tuber mass of Panamera induced by the 100% fertilizer application rate may be due to more luxurious growth, more foliage and leaf area, and higher supply of photosynthates which result in the production of larger tubers particularly as an influence of N (Sharma and Arora, 1987; Nieto, 2016). Similarly, P and K have various effects on vine growth, tuber formation, tuber bulking, and tuber quality due to their roles in cell division, carbohydrates translocation and starch synthesis and storage in tubers (Hopkins *et al*., 2014; Misgina *et al*., 2016; Nyiraneza *et al.*, 2017; Alemayehu *et al*., 2020; Atanaw and Zewide, 2021; Kumar *et al*., 2021). Other studies also found a strong interaction between different potato cultivars and fertilizer application (Love *et al*., 2005; Kumar *et al*., 2009; Jasim *et al*., 2013; Fernandes and Soratto, 2016; Xing *et al*., 2022). The observed results for potato yield under 0% fertilizer application rate are contrary to expected outcomes where plants subjected to nutrient stress generally have lower yields (Oliveira *et al*., 2020; Jovovic *et al*., 2021). Additionally, longer growing period of Panamera allows for a more extended tuber initiation, enlargement, and maturation phase, resulting in larger and higher-yielding tubers (Khan *et al*., 2019; Stark *et al*., 2013). The low fresh tuber mass of Tyson across all fertilizer application rate can be attributed to its genetic trait of limited active leaf growth duration (figure 3.3C) to develop a robust canopy of leaves, which is important for maximizing photosynthesis and capturing sunlight (Lahlou *et al.,* 2003; Getie *et al.,* 2018; Asnake *et al*., 2023). Therefore, it was expected that Sababa and Tyson would have lower yield due to their shortened and lower intercepted photosynthetically active radiation which negatively impact the partitioning of assimilates to tubers (Lahlou *et al*., 2003).

c. Fertilizer application and soil cover induced high potato yields

Previous studies (Li *et al*., 2018; Chen *et al*., 2019; Chang *et al*., 2020; Liu *et al*., 2023), demonstrated that, compared with the traditional flat planting without mulching, organic mulch significantly increases yield of potato on late-maturing and enhance water use efficiency (WUE). In this study cultivars and the application of mulch had no significant interaction effects on potato yield. However, the yield was significantly affected when mulch application was integrated with various fertilizer application rates (Figure 3.10C). Enhancement of the plant hydrothermal micro-environment induced by mulch application significantly increased tuber fresh mass in potato fields when 50 and 0% fertilizer application rates were employed. Mulching increased potato yield by approximately 8 and 16 t/ha under 0 and 50% fertilizer application rates respectively. High yield under mulch and 50% fertilizer application shows that almost the same economic yields may be produced by applying half the recommended fertilizer rates and using mulch to prevent soil water and nutrient losses. When organic materials are used with fertilizer application rates that are reduced by 50 or 75%, good potato yields have been recorded in numerous other integrated nutrient management (INM) studies (Kumar *et al*., 2012; Rajiv, 2014; Singh *et al*., 2018). To achieve optimal crop yields, fertilizer application rates may need to be increased when the soil lacks cover, such as mulch. This is evident from the low potato yields (approx. 23 t/ha) when mulch is not applied under 50% fertilizer application. This is due to the high likelihood of bare soil experiencing increased evaporation and volatilization. By moderating soil temperature, mulching conserves soil moisture and increases soil nutrient availability by reducing ammonia volatilization, which is critical for tuber enlargement and preventing stress-related yield losses (Li *et al*., 2018; Qu *et al.,* 2019; Liu *et al*., 2023).

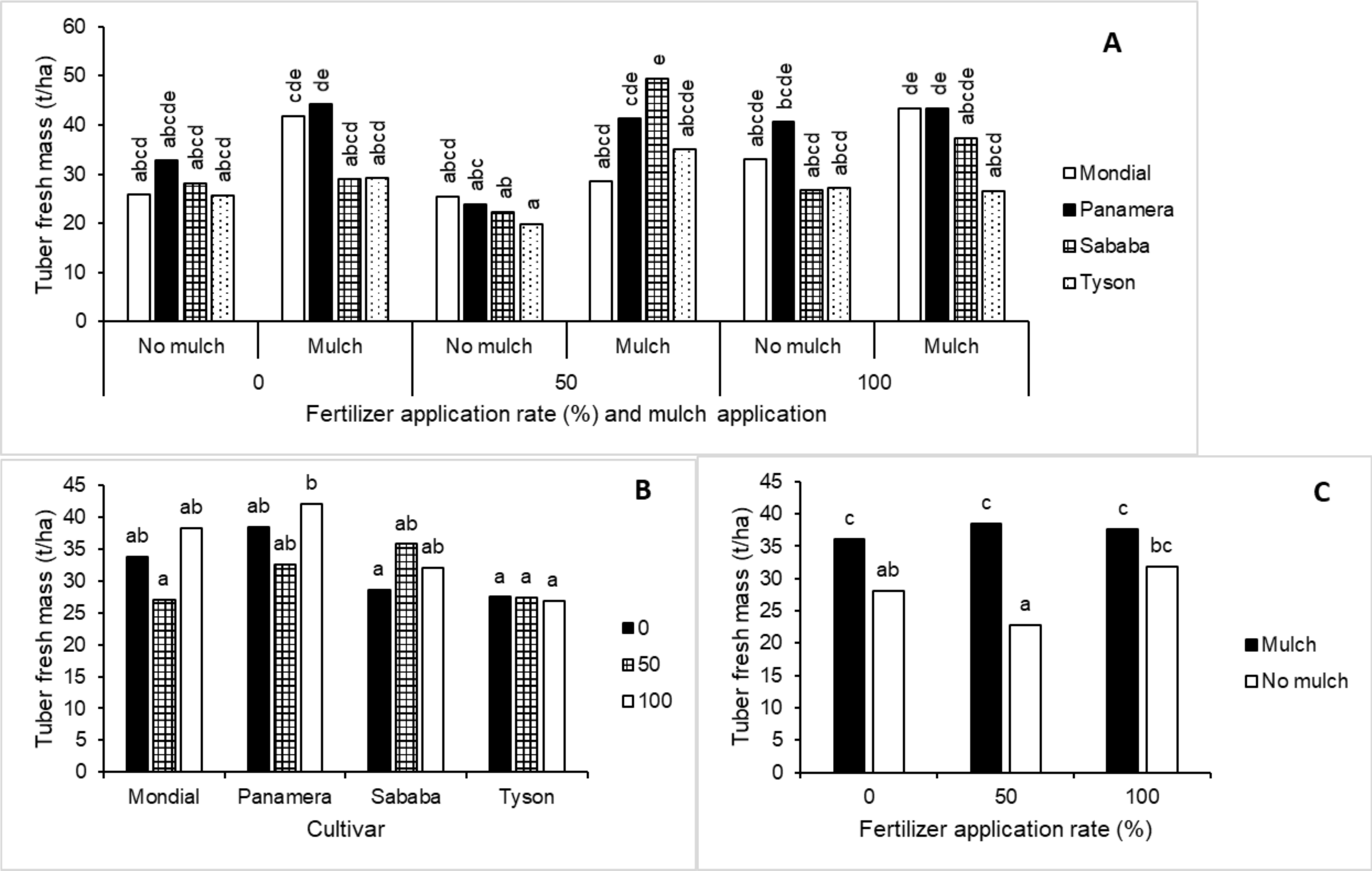

Figure 3.10: Changes in potato yields as a function of integrating various fertilizer application rates, mulch application and various selected cultivars (A) in potato fields under irrigated conditions. Secondary interaction effects of various fertilizer application rates with genetically different cultivars (B) and mulch application (C) on potato yields. Treatments with the same letter are not significantly different at p≤0.05.

3.3.2.4 Number of tubers

Assessing the yield components, changes in the number of tubers as a function of integrating mulch and fertilizer application was significant (Figure 3.11). The interaction effect of mulch application with 0 and 50% fertilizer application rates significantly surpassed the number of tubers in 0% fertilizer application rate without mulch treatment by 42.10 and 40.98 % respectively. These findings coincide with those of Samad *et al*. (2014) who found that the application of mulch and inorganic fertilizer increased the number of tubers. This further suggests that plants at 0% fertilizer application rates without soil cover were vulnerable to water and nutrient stress because of possible losses that occur under bare soils. The low number of tubers under 0% fertilizer application rate without soil cover is also related to suppressed tuber initiation due low canopy cover under the same treatment (Figure 3.5). During tuber initiation stage, carbohydrates produced in the foliage are utilized for stolon growth and the initiation of the tuberization (Libuy, 2006). Leaf area influences photosynthesis and plant growth, by determining light interception through the leaf surface, morphology, and orientation (Paradiso and Proietti, 2021). Therefore, low canopy cover may result in insufficient light exposure, which slow down photosynthesis and decreases the amount of carbohydrates translocated to the stolon growing tips. Under such circumstances plants would not be able to support the growth of as many tubers, and those that do form might not reach their full potential in terms of size and number.

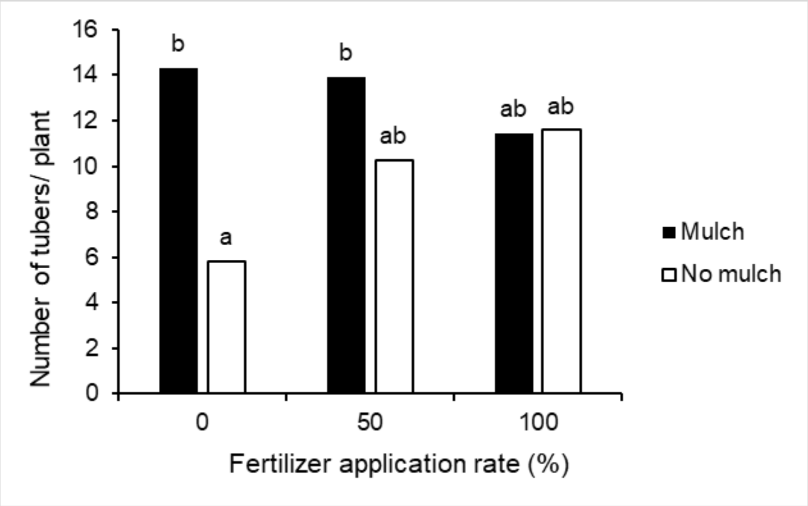

Figure 3.11: Changes in the number of tubers per plant as influence by the integration of mulch and fertilizer application in potato fields under irrigated conditions. Treatments with the same letter are not significantly different at p≤0.05.

3.4 Conclusions and recommendations

The study was conducted to investigate the interactive effect of potato cultivar selection, organic mulch application, and varying soil fertility levels on potato growth and yield under irrigated conditions. Study findings indicated that integrated nutrient management centred on cultivar selection, mulch application and fertilizer application rates significantly affected potato tuber yields. Significantly higher tuber yields were obtained from Panamera cultivar when mulch was applied with the combination of 50% recommended fertilizer application rates. Moreover, the combination of 100% recommended fertilizer application rates, mulching and Panamera yielded comparable tuber yields as that of 50% recommended fertilizer application rates, mulching and the Panamera cultivar. This suggest that it is possible for farmers to reduce fertilizer application from the recommended rates without compromising their potato yields. The primary interaction of cultivar selection, fertilizer application rates and mulch application insignificantly affected growth components and number of tubers. However, the secondary interaction of fertilizer application rate and mulch application significantly affected maximum canopy cover and number of tubers. Potato fields where fertilizers and mulch were not applied produced significantly lower canopy cover and number of tubers. Additionally, secondary interaction of Panamera and Mondial with mulch application showed significantly higher shoot dry biomass. The maximum canopy cover and shoot dry biomass are desirable trait that are major determinants of potato tuber yield. Season longevity influences yields and nutrient uptake of potatoes. Cultivars with a longer growing season showed significantly better growth and yield characteristics than early maturing cultivars. Panamera, a late-maturing cultivar, had a longer period of nutrient uptake and biomass accumulation, which contributed significantly to the overall higher tuber yield. Soil cover inclusion improves growth and yields, and nitrogen utilisation. Mulch application tended to significantly increase time to maturity, maximum canopy cover, biomass accumulation and total tuber yield. It has been shown that mulching can greatly boost the yield of potato tubers grown under 50% fertilizer application, to the point where the yield is comparable to 100% fertilizer, mulch or not. This further supported the need for farmers to look into INM to reduce the fertilizer application from the recommended rates and minimize nutrient losses while optimizing their yields. Therefore, farmers can look into integrating cultivar Panamera, 50% recommended fertilizer rate and mulching to produce sustainable potato yields. However, this experiment relied on a single site and planting season. Perhaps this experiment could be improved by including different agro-climatic zones.

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CHAPTER 4: POTATO TUBER SIZE, DRY MATTER ACCUMULATION AND NITROGEN USE EFFICIENCY RESPONSES TO INTEGRATED NUTRIENT MANAGEMENT CENTRED ON FERTILIZER APPLICATION RATES, SOIL COVER AND CULTIVAR SELECTION

ABSTRACT

Tuber quality and nitrogen use efficiency (NUE) in Limpopo potato growing areas is limited by poor soil fertility, which is caused by soil degradation, poor fertilizer application and management, and high temperatures that increase soil evaporation and volatilization. This study aimed to assess the potential of integrating cultivar selection, mulch and fertilizer application in improving tuber quality and NUE. The experiment was carried out as 3 x 2 x 4 factorial layout, arranged in a completely randomized design (CRD). Treatment factors were: three N fertilizer application rates (control, 120 kg N/ha, and 240 kg N/ha), two soil cover levels (lucerne grass mulch and no mulch), and four potato cultivars (Mondial, Sababa, Panamera, and Tyson). Crop data collected included tuber grading based on tuber size, tuber dry matter, and NUE. Panamera produced significantly higher dry matter accumulation, proportion of medium and large tubers (22, 38, and 36%, respectively) compared to the other potato cultivars. The percentage of large tubers tended to increase with an increase in fertilizer application rates and mulch application. Significantly higher NUE (72%) was obtained from Panamera cultivar when mulched was applied with the combination of 0% recommended fertilizer application rate. The findings of the study further indicated that NUE decreases linearly with increasing N application. The application of 50% fertilizer recommended rate had a significantly higher NUE (31.28%) than 100% recommended fertilizer application rate (19.78%). High tuber quality and NUE associated with Panamera was linked to its extended period of nutrient and water uptake that supported the development of tubers. Low NUE in fertilized potato fields is thought to be caused by sandy soils and heavy summer rains, which favors N leaching particularly under N saturated soils. Therefore, farmers can look into integrating cultivar Panamera, mulch application and 50% fertilizer recommended rate to increase N uptake while optimizing yields. This recommendation is yet to be tested under low rainfall conditions in Limpopo potato growing regions.

Keywords: potato cultivars, fertilizer rates, mulching, poor soil fertility, tuber quality, NUE

4.1 Introduction

Potatoes (*Solanum tuberosum* L.) are one of the staple crops grown worldwide due to their high yields and unique nutritional contribution (Mystkowska *et al.*, 2023). However, the production of potato depends on the choice of cultivar, weather conditions, fertilization, and cropping systems (Naumann *et al.*, 2020; Mystkowska *et al.*, 2023). In the Limpopo Province, which is South Africa's largest potato producer, potatoes are typically grown on coarse sandy soils with low water-holding capacity, making nutrients, particularly N, prone to losses through leaching (Vosloo, 2021; Swafo and Dlamini, 2023). The problem of nutrient leaching is most severe in areas with sandy soils and heavy rainfall or frequent irrigation. Sandy soils usually have low nutrient retention and 20–80% of applied nutrients or chemicals leach or runoff to ground and surface water (Maltas *et al.*, 2018; Matichenkov *et al.*, 2020). This is exacerbated by the shallow root system of potato crop which not only leads to inefficient use of nutrients but also increases the risk of nutrient losses through leaching (Ruza *et al.*, 2013; Koch *et al.*, 2020). In addition to environmental factors reducing nutrient uptake by crops, the high temperatures prevailing in Limpopo province cause further nutrient losses through ammonia volatilization (Meisinger and Jokela, 2000; Phophi *et al.*, 2020). Aside from high fertilizer costs which limit nutrient application, farmers also face higher production costs due to these nutrient losses from runoff, leaching, and volatilization. Given the high cost of inputs like fertilizers, it is essential to optimize their utilization to improve crop productivity and nutrient use efficiency.

Major effects of declining soil fertility due to environmental losses and inadequate fertilizer application include not only low yields, loss of agrobiodiversity, and soil loss, but also low nutrient use efficiency in cropping systems (Alemayehu *et al.*, 2020; Setu, 2022). Efficient nitrogen use ensures optimal plant growth, minimizes nitrogen losses, lowers input expenses, and supports long-term soil fertility (Perchlik and Tegeder, 2017; Anas *et al.*, 2020). However, plants only absorb 40-50% of the 180-240 kg N/ha of fertilizers required for a good tuber yield (35-45 t/ha) in potato production; the remaining N is lost to the environment (Trehan and Singh, 2013). The losses are caused by the susceptibility of nitrogen to volatilization and leaching as well as the underdeveloped root system of potato plant, which limits the plant's ability to absorb nutrients from deeper soil layers and lowers the NUE. (Iwama, 2008; Milroy *et al*., 2019; Chattha *et al*., 2023). Plants generally take up N from the soil, which are assimilated into various organic compounds, including amino acids, which are the building blocks of proteins in the tubers (potato storage organs) for the production of dry matter (Perchlik and Tegeder, 2017). Therefore, the growth, development, and quality of potato tubers, including their dry matter content and size, might be directly reduced by the low NUE caused by environmental losses and low N application (Fang *et al*., 2023). While the dry matter content of potato tubers is an important quality characteristic that directly impacts processing and the quality of the final product in various potato industries, the size distribution for a grower has a major impact on the marketability of their crop (Nkhase, 2019; Stefaniak *et al*., 2021). Therefore, improving the potato plant's ability to absorb nutrients is crucial for optimizing tuber quality.

A solution to these problems involves the incorporation of potato cultivars in integrated nutrient management that use N highly efficiently and produce high yields with reduced N input (Perchlik and Tegeder, 2017). Reducing fertilizer input and breeding plants with increased NUE is currently one of the key goals of research on plant nutrition (Hirel *et al*., 2007). Additionally, to reduce N losses by moderating soil temperatures, mulching reduces nutrient losses, particularly N losses caused by volatilization (Shi *et al.,* 2022). This study examined tuber size distribution, dry matter accumulation, and NUE in response to integrating cultivar differences, different fertilizer application rates, and soil cover.

4.2 Material and method

4.2.1 Sourcing of plant materials

Potato tubers for post-harvest analysis were harvested at physiological maturity from a field trial that was carried out at University of Limpopo Sykerfuil Experimental farm, near Polokwane in the Limpopo province of South Africa (as outlined in Chapter 3). To determine tuber size distribution and dry matter accumulation, three plants per treatment were randomly harvested from the experimental rows at physiological maturity and the harvested tubers were hand washed with tap water to remove any foreign material such as soil. Three more plants per treatment combination was randomly harvested from the experimental rows at physiological maturity and the harvested tubers were hand washed with distilled water (to eliminate contaminants that may interfere with the accuracy of the results) for tuber nutritional analysis.

4.2.2 Experimental design and layout

The post-harvest analysis experiment was carried out as 3 x 2 x 4 factorial layout, arranged in a completely randomised design (CRD) due to lack of blocking for tuber analysis conducted under laboratory conditions. Treatment factors were: three N fertilizer application rates (control, 120 kg N/ha, and 240 kg N/ha), two soil cover levels (lucerne grass mulch and no mulch), and four potato cultivars (Mondial, Sababa, Panamera and Tyson). Nitrogen (N), potassium (K) and phosphorus (P) fertilizer application rates for 240 kg N/ha were applied as recommended application to obtain the yield target of 60 t/ha (Chapter 3 section 3.2). All N, P and K fertilizer application rates for 120 kg N/ha were applied as half of what was recommended for the 240 kg N/ha. Mulch application was achieved through total soil surface cover using lucerne grass mulch. Differences in, and characterization of potato cultivars is as described in Chapter 3 (section 3.2).

4.2.3 Data collection

4.2.3.1 Tuber grading

Tuber grading based on tuber size or weight is important to evaluate the quality parameters of potato (Nowroz *et al.*, 2021). In this present study, tuber grading was conducted based on tuber size. Each tuber's size was determined by using a Vernier calliper to measure its diameter along the principal axes. The following tuber size categories were used to classify tuber sizes: large ≥ 75 mm, medium 55-75 mm, and small ≤ 55 mm (Ekin, 2013).

4.2.3.2 Dry matter content

The harvested tubers for tuber grading were cut into smaller thin slices and oven dried at 75 °C until a constant dry weight was obtained to determine the dry matter. The dry matter was then calculated using the following formula:

$$DM\ (\%) = \frac{Dry\ weight\ (g)}{Fresh\ weight\ (g)} \times 100$$

4.2.3.3 Nitrogen use efficiency (NUE)

Nitrogen use efficiency (NUE) is typically calculated as the yield per unit of N resource available to the plant (Moll *et al*., 1982). However, the method of NUE determination depends on the crop species and the objective of the study (Getahun *et al*., 2020). To account for soil N contributions to the plant components in this study, a soil-based indices was used to calculate NUE (%) as a ratio of N taken up by the crop in relation to soil available N prior to planting plus N supplied through fertilizer application (Moll *et al*., 1982):

$$\text{Nitrogen use efficiency (\%)} = \frac{Total\ plant\ nitrogen}{Soil\ nitrogen + Applied\ nitrogen}$$

Tuber nitrogen uptake (kg N/ha) was calculated by multiplying the tuber dry matter yield (kg/ha) by the tuber N content.

Soil samples were taken after harvest at the centre of experimental rows of all the treatment combination. One soil sample per treatment was collected with an auger from the Orthic A (0-0.3 m) and Red Apedal B (0.3-0.8 m) horizons. The soil samples were transported to Cedara College of Agriculture for soil N analysis. Colorime-Tric methods were used to measure nitrogen. The recommended N application rate was based on achieving a yield target of 60 t/ha and not on available soil N (Table 4.1).

Table 4.5: Soil N and applied N in potato fields under irrigated conditions of the Sykerfuil experimental farm.

Soil N	50% N application	100% N application
……….……………	kg/ha	…………….......
60	120	240

Three medium-sized tubers from the harvested tubers were selected per treatment and were peeled and then cut into thin slices. The slices were then oven dried at a temperature of 45 °C for 48 hours. The samples were ground with an electric micro plant grinding machine and used to conduct tuber N analysis at Cedara College of Agriculture. An inductively coupled plasma optical emission spectrometer Vista-MPX 2004 (Varian, Mulgrave, Australia) was used to analyse tuber N content. The analysis was conducted against known standard solutions of the elements, and a blank (deionised water) (Ngobese *et al.*, 2017).

4.3 Results and discussion

Cultivar differences had a significant influence on tuber dry matter, the percentage of small, medium and large tubers. Fertilizer application rates and mulch application individually indicated to significantly affect the percentage of large tubers. The primary integration (F x C x M) indicated to have a significant effect on NUE. Secondary integration (F x C, F x M, and C x M) had a significant impact on NUE. Different fertilizer application rates showed a highly significant influence on NUE.

Table 4.6: Summary analysis of variance indicating effect of integrating fertilizer application rates, mulch application, and different potato cultivars on tuber size grading, tuber dry matter and NUE.

Source of variance	P-values				
	DM	ST	MT	LT	NUE
Fertilizer application rate (F)	0.235	0.196	0.107	**0.031**	**<0.001**
Cultivar (C)	**0.030**	**<0.001**	**0.023**	**<0.001**	0.078
Mulch application (M)	0.246	0.138	0.555	**0.023**	0.102
F x C	0.423	0.707	0.422	0.085	**<0.001**
F x M	0.086	0.505	0.083	0.764	**0.047**
C x M	0.423	0.773	0.611	0.944	**0.053**
F x C x M	0.155	0.266	0.693	0.166	**<0.001**

Note: DM= Dry matter, ST= Small tubers, MT= medium tubers, LT= Large tubers, and NUE= Nitrogen use efficiency

4.3.1 Tuber grading based on size

4.3.1.1 Cultivar differences in the size of tubers

The observed results show that the selected cultivars varied significantly in tuber size distribution (Figures 4.1). Tuber grading of cultivar Tyson, Mondial, and Sababa followed a similar pattern, such that the percentage of small tubers was higher mainly at the expense of medium and large tubers. On average 53, 65, and 70% of the total number of tubers in Sababa, Mondial, and Tyson, respectively, were small-sized tubers while 23, 14, and 11% of the tubers respectively, were large. Panamera indicated to have a higher proportion of large and medium-sized tubers (38 and 36%, respectively) than the other cultivar. The difference in very small-sized and large-sized tubers could be associated with the crop maturity, inherent characteristics of potato cultivars and environmental factors (Gebreselassie *et al.*, 2016; Eaton *et al.*, 2017; Nowroz *et al.*, 2021; Asnake *et al.*, 2023).

The shorter growing period expressed by Sababa means that the cultivar had less time to allocate energy and nutrients for tuber development (Nieto, 2016). As a result, the potatoes tended to be smaller in size compared to those from longer-season cultivars such as Panamera (Aliche *et al.,* 2019). Panamera also expressed a lower total number of tubers, which may have contributed to each tuber receiving a larger share of available resources, allowing individual tubers to grow larger in size. Sababa, Tyson, and Mondial expresed a higher total number of tubers, potentially causing competition for limited resources, leading to smaller individual tuber sizes due to smaller share of available nutrients and energy (Kumar *et al*., 2007; Patel *et al.,* 2008). A survey by Badenhorst (2014), revealed a 70% preference for medium and large-sized potatoes by South African consumers, which indicates potential if cultivar Panamera was to be sold in fresh produce markets.

4.3.1.2 Fertility induced differences in large tuber distribution

Large tubers not only differed significantly between cultivars, but also in terms of different fertilizer application rates and mulch application solely (Figure 4.1). The percentage of large tubers tended to increase with an increase in fertilizer application rates and the presence of mulch. Application of 100% of the recommended fertilizer application rate surpassed the 0 and 50% fertilizer application by 17 and 21% respectively, with regards to large-sized tubers. The applied NPK fertilizer had a significant influence on the tuber diameter which correspond with large sized tubers (Eremeev *et al.,* 2009; Misgina *et al*., 2016). In contrast, Rosen and Bierman (2008) reported that incremental P rates had no effect on the percentage of marketable tubers and attributed this to an increase in the number of small tubers happening concurrently with a reduction in the percentage of large tubers as P rate increased.

4.3.1.3 Effect of mulching on large tuber distribution

In the present study, mulch application increased the proportion of large tubers by 24% (Figure 4.1). Mulching modifies the temperature and moisture conditions of the soil, which affects the production of quality size tubers by improving water and nutrient uptake, which increases the growth of individual potato tubers (Kiptoo *et al.*, 2018; Bharati *et al.,* 2020; El-Wahed *et al.*, 2020; Sekhon *et al.*, 2020; Nowroz *et al.*, 2021).

4.3.1.4 Tuber size distribution under the integration of various cultivars, mulch application and various fertilizer application rates

The bigger interaction of cultivars, mulch application and fertilizer application rates (Figure 4.1) indicated that the cultivar Panamera had a higher proportion of large tubers at 100% fertilizer application with and without mulch, while the lowest proportion of large tubers were observed from Tyson and Mondial, when subjected to 0% fertilizer application rate without mulch. The high proportion of large tubers of Panamera under 100% fertilizer application with and without mulch translated to lower proportion of small tubers in these treatments. Tyson and Mondial also showed the highest proportion of small tubers at 0% fertilizer application without mulch. This suggest that when there is a high percentage of small tubers, the potato plant’s energy resources are allocated towards producing smaller tubers rather than larger tubers.

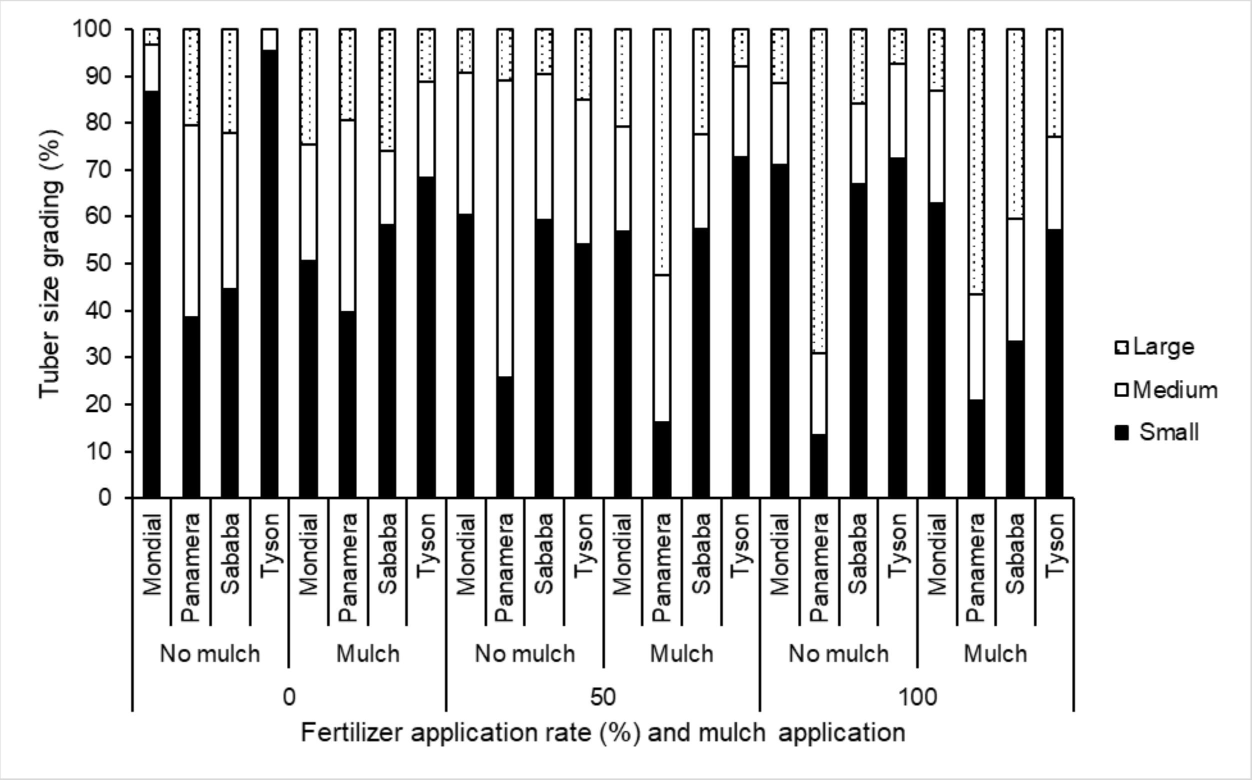

Figure 4.1: Changes in tuber sizes as a function of the integration of various cultivars, mulch application and various fertilizer application rates effect on tuber grading by size in potato fields under irrigated conditions.

4.3.2 Tuber dry matter as affected by cultivar differences

The quality of potato tubers is often referred to as external and internal quality (Mohammed, 2016). Internal quality is determined by many traits of which the most important are dry matter content, type and amount of starch, sugar and protein content (Van Eck, 2007). In this current study, dry matter production and allocation to the tubers varied significantly between potato cultivars (Figure 4.2). Numerous studies have reported significant variation in dry matter partitioning to the tubers among various cultivars (Geremew *et al.*, 2007; Mohammed, 2016; Naeem and Caliskan, 2020; Ngobese *et al.*, 2022).

The distribution of dry matter among the tubers in Panamera significantly exceeded the dry matter distribution in Sababa by approximately 4%. Early maturing potato cultivar have generally lower dry matter content than medium- and late-maturing potatoes (Gray and Hughes, 1982). Given that Panamera is a cultivar with a late maturation, this supports its prolonged dry matter allocation to the tubers (Geremew *et al.*, 2007). Furthermore, potato plants derive 90–95% of their dry matter from photosynthesis-assimilated products, and the distribution of assimilated products in the organs varies with the growth and development process of potatoes, suggesting that the high-robust canopy development tendency of Panamera contributed to its accumulation of dry matter (He *et al.*, 2020). In contrast, Ngobese *et al.* (2022) reported the highest dry matter content of an early maturing cultivar (Innovator), which surpassed the other late and medium-late cultivars (Panamera and Mondial), among others.

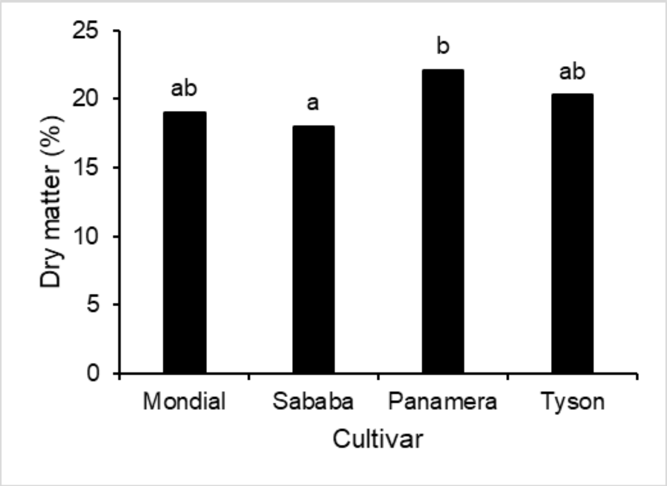

Figure 4.2: Tuber dry matter accumulation of different potato cultivars. Treatments with the same letter are not significantly different at p≤0.05.

4.3.3 Nitrogen use efficiency (NUE)

4.3.3.1 Decline in NUE of potato crops with increasing N application

Increasing fertilizer application rates on potato fields significantly decreased the NUE (Figure 4.3A). Lack of fertilizer application in the control plots increased NUE by approximately 22 and 34% relative to applying half and full of recommended fertilizer application rates respectively. The very low NUE when 50 and 100% fertilizer application rates are employed suggest that only 20-30% of the applied N was taken up by the crops and the 70-80% was either left in the soil or lost to environment by pathways such as leaching or volatilization (Gao *et al.*, 2018). The application of 50% fertilizer recommended rate showed significantly high NUE compared to 100% fertilizer recommended rate. This basically showed that soils that are saturated with N tend to lose more N than unsaturated N soils. This study was conducted in coarse textured soils which are highly susceptible to N losses through nitrate leaching particularly under increased N application rates, resulting in high reduction of NUE (Zebarth *et al*., 2004; Gao *et al*., 2018). Abundant summer precipitation that was observed during tuber bulking phase (as shown in Figure 3.1) where the highest amount of N is needed, possibly favoured the leaching of N (Ruza *et al*., 2013; Koch *et al*., 2020). Similarly, other studies have reported that NUE decreases linearly with increasing N application rate (Darwish *et al*., 2006; Fontes *et al*., 2010; Mustonen *et al*., 2010; Nieto, 2016); suggesting that research efforts to improve NUE of crop production must consider the reduction of N application rate while optimizing potato yields. The very low NUE value when 100% fertilizer application rate is employed can also be attributed to excessive N application, as 240 kg/N ha was applied to soils that already contained 60 kg/N ha, giving a total of 300 kg/N ha. It can therefore be suggested that the recommendation for the N application rate should be based not only on the yield target, but also on the amount of N in the soil.

4.3.3.2 NUE under the integration of various fertilizer application rates and various cultivars

The interaction of increasing fertilizer application rates and the selected cultivars on potato fields significantly decreased NUE (Figure 4.3B). The observed differences were driven by highly significant reductions in NUE when fertilizer application rates were employed (Figure 4.3A), rather than the differences in the selected cultivars which did not result in any statistically significant alterations in NUE. High application of N increases dry matter partitioned to shoots at the expense of tubers in some of the cultivars (Nkhase, 2019). This reduces tuber dry matter which can decline with NUE. Potato is held to have poor NUE due to a poorly developed root system (Milroy *et al*., 2019). However, NUE of Panamera significantly surpassed NUE of Tyson by approximately 19% when 0% fertilizer application was employed. This can be attributed to a greater root biomass and longer growing period of late maturing cultivars, allowing them more time to absorb and utilize nitrogen from the soil compared to early cultivars (Iwama, 2008; Ruza *et al*., 2013; Getahun *et al*., 2020). Greater root biomass cannot be used as the sole indicator to increase NUE as indicated in this study that although the selected cultivars varied in root biomass, they did not induce any significant differences in NUE. Therefore, breeders must look at the potential candidate genes for improving

NUE in potato particularly in potato roots whereby high-affinity nitrate transporters are the key candidate genes for manipulation in N uptake and transport (Tiwari *et al*., 2020).

4.3.3.3 NUE under the integration of various fertilizer application rates, various cultivars and mulch application

The integration of soil fertility, mulch application and cultivar differences indicated to have a significant impact on NUE (Figure 4.3C). The integration of Mondial and 100% fertilizer application rate without soil cover resulted in the lowest NUE (13%). Mondial had a significantly lower NUE compared to Panamera and Sababa when there was a lack of fertilizer and mulch application. However, when mulched was applied under 0% fertilizer application rate, Mondial and Panamera indicated to have the highest NUE. This indicate that mulching does reduce N losses through volatilization and conserve the N in the root zone (Kader *et al*., 2019) although other losses of N can still occur under mulching through leaching, hence mulch application alone did not induce any significant impact on NUE.

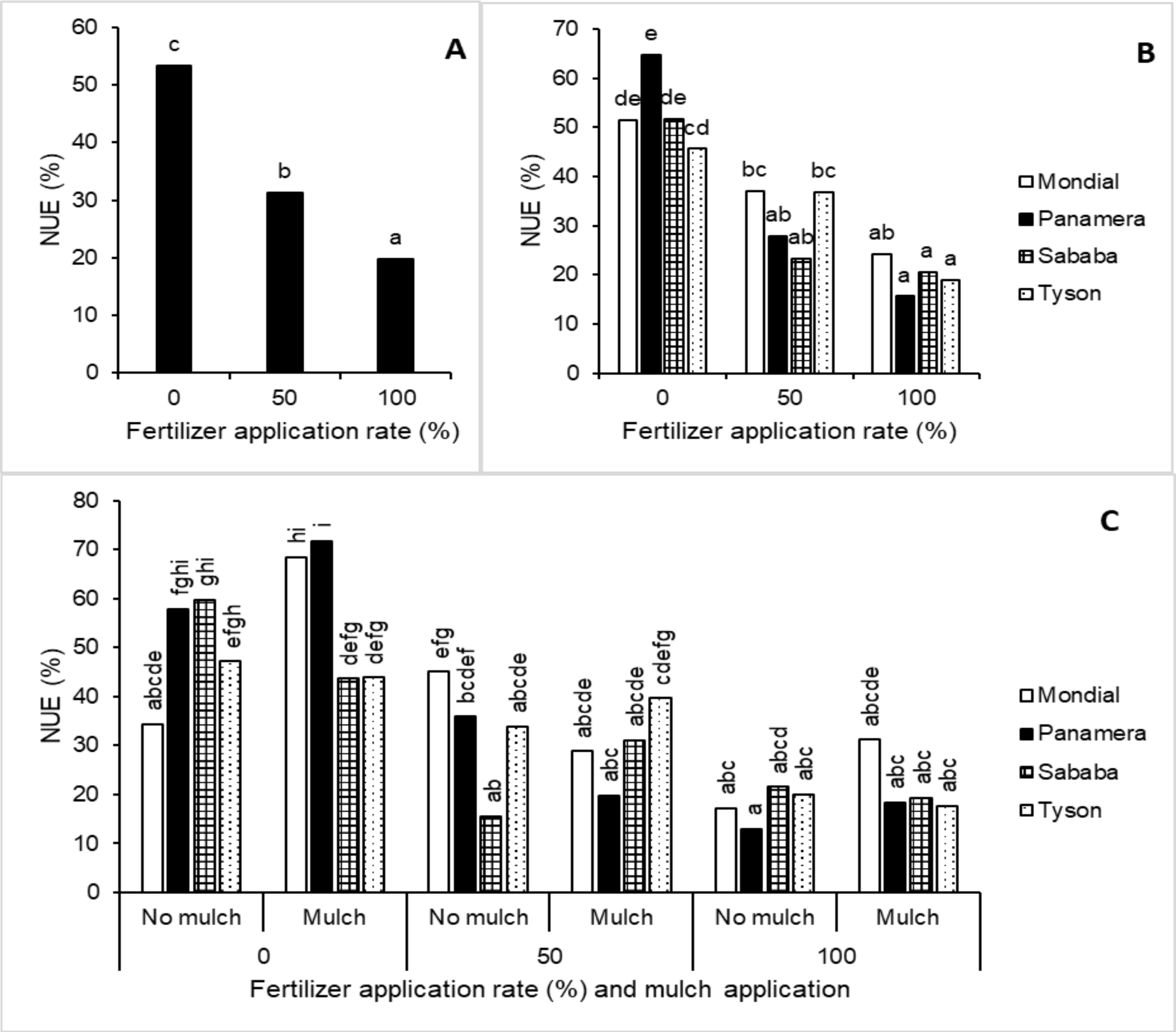

Figure 4.3: Changes in NUE as a function of various fertilizer application rates (A), integration of various fertilizer application rates with different cultivars (B), and the integration of fertilizer application rates, mulch application and selected cultivars (C) in potato fields under irrigated conditions. Treatments with the same letter are not significantly different at p≤0.05.

4.4 Conclusions and Recommendations

This study examined tuber size distribution, dry matter accumulation, and NUE in response to integrating cultivar differences, different fertilizer application rates, and soil cover. The primary interaction of cultivar selection, fertilizer application rates and mulch application insignificantly affected dry mater accumulation and cultivar size distribution. However, cultivar differences significantly affected dry matter accumulation, and highly significantly affected tuber size distribution. Panamera had significantly higher dry matter accumulation, proportion of medium and large tubers compared to other potato cultivars. Study findings further indicated that integrated nutrient management centred on cultivar selection, mulch application and fertilizer application rates significantly affected tuber NUE. Significantly higher NUE was obtained from Panamera cultivar when mulch was applied with the combination of 0% recommended fertilizer application rate. This suggested that in order to maximize production with low soil N, cultivar Panamera may be regarded as a nutrient-efficient cultivar appropriate for incorporation into INM. The findings of the study further indicated that NUE decreases linearly with increasing N application. The application of 50% fertilizer recommended rate had a significantly higher NUE than 100% recommended fertilizer application rate. This indicated that N losses are exacerbated under N saturated soils. Environmental factors such as sandy soils and summer rainfall may have promoted leaching of N applied. Therefore, farmers can look into integrating cultivar Panamera, mulch application and 50% fertilizer recommended rate to increase N uptake while optimizing yields. Moreover, to better estimate NUE, the recommended N application rate must take into account the available N in the soil to reduce to avoid excessive N application.

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CHAPTER 5: GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

5.1 General Discussion

This study set out to examine the potential of integrating cultivar selection, soil cover and fertilizer application rates to reduce the soil fertility-related potato yield gap, maintain high tuber quality and reduce nitrogen environmental losses in potato agricultural systems.

Literature review findings indicated that integrated nutrient management (INM) can maximize potato yield, tuber quality, and limiting nutrient losses without degrading the quality of the soil, thus a likely candidate strategy for lowering excessive use of inorganic fertilizers in potato production. These findings were confirmed by field and post-harvest experiments where yields from 50% recommended fertilizer application rates were comparable to 100% recommended fertilizer application rates when soil cover was incorporated as part of an INM strategy. Moreover, 50% recommended fertilizer application rates exhibited superior nitrogen use efficiency (NUE) compared to full fertilizer recommendation highlighting the additional environmental benefits of reduced inorganic fertilizer application during potato production. Study findings therefore indicated that it is possible to reduce fertilizer application from recommended rates and still achieve comparable yield outcomes, while reducing eutrophication potential to the environment and saving on fertilizer costs. This can be explained by the fact that agricultural systems are maintained in nutrient saturated states in order to meet yield targets (Zhang *et al*., 2012), with minimal application of nutrient loss mitigating factors such as soil cover. Further evidence of maintaining agricultural soils in nutrient saturated states is 7.4-fold increase in fertilizer application over a 40-year period being reciprocated by a lowly 2.4 fold overall increase in yield (Hirel *et al*., 2011). In such intensive agricultural production systems, nutrient losses in potato fields are above 50%, and up to 75% of the applied nutrients (Hirel *et al*., 2011; Mejias *et al*., 2021). This was confirmed by significantly higher nitrogen use efficiency under 50% recommended fertilizer application rate as compared to 100% recommended fertilizer application rates, indicating that fertilizer saturated states tend to lose more nutrients than unsaturated states. The fact that the recommended N application rate was only based on the yield target and did not take into account the available N in the soil contributed to the extremely low NUE under 100% of the recommended fertilizer application rate. This suggested that, in order to prevent applying excessive N, the recommended rates of fertilizer should take the amount of N present in the soil into account.

Literature findings suggested that incorporation of soil cover can be valuable tool to ameliorate soil health, reduce inorganic fertilizer application, and reduce atmospheric nitrogen losses in potato production. This was further supported by findings of significantly superior yields and NUE when organic mulch cover was incorporated into potato production during field trials. Overall, literature and experimental findings suggested that short-term (seasonal) benefits of mulch could lie in reduced nitrogen volatilization that is exacerbated by low nutrient and water holding capacity of coarse structured soils and hot spring/summer temperatures in potato producing regions of Limpopo (Siman *et al*., 2020; Shikwambana *et al*., 2021). Nitrogen volatilization can become more pronounced as temperatures climb above 21°C (Jones *et al*., 2013), indicating that there can be severe N losses in hot regions like Limpopo where summer temperatures can exceed 36°C during the day (Tyasi *et al*., 2022). Given that nitrogen volatilization increasingly becomes significant from 14°C upwards, and is exacerbated in irrigated soils (Dari *et al*., 2019), mulch application should be considered by potato producers in tropical, semi-arid, irrigated conditions as an environmentally friendly yield improvement practice. Mulching introduces additional production costs to the agricultural system, and mulches can be extremely costly depending on type of mulch and other application costs (Iqbal *et al.,* 2020; Fan *et al*., 2023). As such, producers may need to compare the yield and environmental benefits to the costs of mulch application in order to evaluate the suitability of using mulch in their potato fields.

Literature findings suggested that selection for longer potato maturity period can considerably increase potato yields and nutrient uptake. Significantly higher yields, yield quality and nitrogen use efficiency were also observed under field experiments when Panamera (a late maturing cultivar) was included within an integrated management strategy. These experimental findings gave further support to suggestions drawn from the literature review, indicating that maturity length is a vital component of integrated nutrient management in potatoes. Extended growing period length allows for a longer period of photosynthesis, nutrient uptake and tuber bulking in potatoes (Haverkort and Struik, 2015; Nasir and Toth, 2022). Since higher nitrogen uptake can sometimes translate to a lower potato harvest index, through a relatively high canopy to tuber mass ratio, it is critical that selection for a long season cultivar is accompanied by selection for a high harvest index when trying to optimize fertilizer utilization in potato fields.

5.2 General Conclusion

This study set out to assess the potential of integrating cultivar selection, soil cover and different fertilizer application rates as part of an environmentally friendly INM strategy that closes the soil fertility-based potato yield gap. The interaction of different fertilizer application rates, mulch application and various potato cultivars significantly altered yield parameters, tuber quality and nitrogen use efficiency when tested under field conditions. Experimental findings indicated that incorporating reduced fertilizer application (50% of recommended application rate), with soil cover through organic mulch, and planting a late maturing cultivar significantly improved tuber yield, yield grading quality, and nitrogen use efficiency.

5.3 Further Recommendations

A limitation of this study is that it was conducted at a single planting site and growing season. A further study could assess INM centered on cultivar choice, fertilizer application rates and organic soil cover under different agro-ecological regions and replicate it over multiple seasons to validate accuracy and robustness of study findings.

In an effort to reduce inorganic fertilizer application in potato cultivation, the study recommends that current fertilizer recommendation guidelines that only use the target yield to recommend nitrogen application rates be revised to incorporate soil nitrogen concentrations. Study findings suggested that saturating soils with nitrogen increases nitrogen losses and fertilizer costs, without a corresponding increase in tuber yield and tuber quality.

Similarly, to fertilizer application, mulch application introduces additional input costs to an agricultural system. Mulching costs therefore need to be matched against potential yield and environmental benefits using a mulch precision strategy to assess scenario-specific suitability of mulch application in potato production.

When incorporating cultivar selection as part of an INM strategy, late maturing cultivars are recommended in order to extend biomass and nutrient accumulation period.

However, adoption of late maturing cultivars remains difficult under South African settings as the potato industry prefers popular cultivars (e.g. Mondial, Sifra, and BP1) which are not late maturing.

5.4 References

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