

Determining plant spatial arrangement, plant population, and mineral nutrient requirements of
Neoratanenia brachypus (Harms) CA in two contrasting agroecologies: Towards *N.*
brachypus domestication

BY

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**A dissertation submitted in fulfilment of the requirements for an award of the Master of
Philosophy degree in Agronomy**

**Department of Crop Science and Post-Harvest Technology
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Chinhoyi University of Technology**

July 2024

Title

Determining plant spatial arrangement, plant population, and mineral nutrient requirements of *Neoratanenia brachypus* (Harms) CA in two contrasting agroecologies: Towards *N. brachypus* domestication

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THESIS APPROVAL

The undersigned certify that they have read and recommended to the Department of Crop Science and Postharvest Technology, the thesis entitled:

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Declaration

Marilyn W. Kutamahufa, (C15124557Y) has authored this dissertation as an original work. The author has not previously submitted the dissertation nor has it been submitted to any university for any award of degree, diploma, or certificate other than the Chinhoyi University of Technology. I have appropriately acknowledged all the help that I received in my research work and in the preparation of the dissertation itself. I also certify that I have appropriately referenced and acknowledged all information sources and literature in the dissertation.

A handwritten signature in blue ink, appearing to be 'Marilyn W. Kutamahufa', with a long horizontal stroke extending to the right.

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Date...29-09-2024

Dedication

I dedicate this dissertation to my mother, Mrs. Judith Kutamahufa, and my family for their consistent support and faith in me throughout my studies.

Acknowledgements

The candidate acknowledges the Research Council of Zimbabwe and the Ministry of Higher and Tertiary Education, Innovation, Science and Technology Development for their financial support through the Zimbabwe Manpower Development Fund (ZIMDEF). I greatly appreciate Prof. Arnold B. Mashingaidze, Prof. Chrispen Murungweni, and Dr. Zedias Chikwambi for their supervision, their constant support and guidance throughout the research period. Their patience, motivation, and enormous knowledge were very precious during the research, greatly assisting me in shaping the research process and dissertation write-up. The Crop Research Coordinator, Dr. N. Mashavakure, and Chairperson of the Department, Dr. K. Musiyiwa, are highly appreciated for their kind help in accessing Chinhoyi University of Technology (CUT) resources, their constructive criticism, wise counsel, and encouragement.

Special gratitude also goes to all the members of the CUT farm and the Department of Crop Science and Post-Harvest Technology for their practical help. Miss Linda Nhandara, Mr Alex Masheka and Ms Rumbidzai Makanda are among the laboratory technicians who assisted me. I sincerely acknowledge my friends, Denver Chisodza, Tafadzwa Mahurede and Yolanda Mutinhima for their emotional support. My fellow students, Tinotenda Kaseke and Lucy Chipondoro, are also appreciated for their unwavering support in carrying out the experiments. The author is indebted to all members of CUT Graduate Studies, CUT student affairs and the Zanamwe family in their capacities and for their material support.

Finally, I would like to extend my heartfelt gratitude to my siblings for their unwavering support and encouragement throughout my study program. I have come to realise that success is seldom achieved alone; it is only possible with the help and support of those around us. Therefore, I thank everyone who has contributed to my journey, even if they aren't named individually. Above all, I am deeply grateful to the Almighty Jehovah for blessing me with the opportunity to undertake this study.

Abstract

Neorautanenia brachypus (Harms) CA Sm. is a wild, tuberous, perennial herb that many smallholder farmers have adopted as a drought survival feed for livestock in the south-eastern lowveld of Zimbabwe. To enable the commercial production of *N. brachypus*, there is a need for its domestication. Therefore, the objective of this study was to determine the plant spatial arrangement, plant population, and mineral nutrient requirements of *N. brachypus* to facilitate its domestication. A systematic review which assessed the effect of N, P and K fertilisers on the growth and yield of root and tuber crops (RTCs) showed variable responses ranging from no responses, positive and negative responses depending on soil fertility, climatic conditions, plant spacing and population density, species of RTC and other factors. There is no or very little research that has been done on plant spatial arrangement, population, and nutrient requirements of *N. brachypus* to enable agronomic recommendation domains to be produced towards its domestication, motivating this study. The first experiment was organised as a 3×2 factorial in a randomised complete block design (RCBD) with inter-row spacing (0.45, 0.60, and 0.75 m) and in-row plant spacing (0.30, and 0.45 m) as factors, replicated three times, at a high rainfall and low fertility arenosol sandy soil (Zvimba site) and a low rainfall high fertility eutric vertisol soil (Chikombedzi site) over two growing seasons (2020/21 and 2021/22). The second experiment employed a nutrient omission design, to evaluate the effects of 145 kg ha^{-1} N, $128 \text{ kg ha}^{-1} \text{ P}_2\text{O}_5$ and $121 \text{ kg ha}^{-1} \text{ K}_2\text{O}$ straight fertilisers and their combinations (N&P, N&K, P&K and N, P&K) on the growth and yield of *N. brachypus*. The third experiment, a 4×4 factorial in an RCBD, tested the effect of application rate of NPK (7% N, 14% P_2O_5 , 7% K_2O) viz., 0 kg ha^{-1} , 75 kg ha^{-1} , 150 kg ha^{-1} , 300 kg ha^{-1} and four ammonium nitrate (AN, 34.5% N) fertiliser application rates viz., 0 kg ha^{-1} , 75 kg ha^{-1} , 150 kg ha^{-1} , 300 kg ha^{-1}). The results showed that, at the sandy infertile, Zvimba site, there were significant interactions ($P < 0.05$) between inter-row and in-row spacing on tuber length, diameter, and yield, which showed that the effect of in-row-spacing on tuber length, diameter and yield depended on inter-row-spacing. Tuber length, diameter, and yield did not significantly differ with an increase in inter-row spacing at 0.45 m in-row spacing. In contrast, tuber length, diameter, and yield were highest at the intermediate inter-row spacing (0.60 m) and were significantly lower at the narrow (0.45 m) and wide (0.75 m) inter-row spacing at 0.30 m in-row spacing. The highest tuber length, diameter and yield were obtained at 0.60 m inter-row x 0.30 m in-row with a plant population density of $55\,555 \text{ plants ha}^{-1}$ which is recommended, from the results of this study, for the arenosol sandy soil Zvimba site. At the more fertile deep black clay eutric vertisol soil

Chikombedzi site, averaged across in-row spacing, tuber length (121.17 mm), diameter (24.27 mm) and yield (2150 kg ha⁻¹) was significantly higher ($P < 0.01$) in the narrow inter-row (0.45 m) spacing than the intermediate inter-row (0.6 m) spacing and the wide (0.75 m) inter-row spacing. Therefore, the narrow inter-row (0.45 m) spacing is recommended for the heavy soil site of Chikombedzi, in combination with an in-row spacing of between 0.3 m and 0.45 m depending on farmer circumstances with respect to the availability of seed, use of machinery and other factors. The results of the nutrient omission trial showed that the application of 145 kg ha⁻¹ N significantly reduced tuber yield ($P < 0.05$) by 63% and 62.5% at the Zvimba site and at the Chikombedzi site, respectively, compared to the control without fertiliser. Application of 128 kg ha⁻¹ P₂O₅ produced a similar yield to the control at the Zvimba site and increased yield by 34% compared to the control treatment at the Chikombedzi site. There was no significant difference in tuber yield between the control and the 121 kg ha⁻¹ K₂O treatment at the Zvimba and Chikombedzi sites. Combinations of N&P, N&K, P&K, and N, P&K straight fertilisers did not significantly increase tuber yield when compared to the control at the Zvimba and Chikombedzi sites. There was a significant interaction ($P < 0.05$) between compound 7%N, 14%P₂O₅, 7% K₂O fertilizer and top-dressing ammonium nitrate (AN) (34.5% N) fertiliser application rates at the arenosol soil Zvimba site and the eutric vertisol Chikombedzi site on *N. brachypus* tuber yield. The interactions showed that the achievement of maximum tuber yield depended on the specific combination of rate of application of basal NPK fertiliser plus top dressing AN fertiliser at each site. At the sandy arenosol Zvimba site, the highest tuber yield was attained when 0 kg ha⁻¹ compound NPK × 75 kg ha⁻¹ AN was applied and when 150 kg ha⁻¹ compound NPK fertiliser plus 150 kg ha⁻¹ AN fertiliser was applied. At the deep black clay eutric vertisol Chikombedzi site, the highest tuber yield was attained when 150 kg ha⁻¹ compound NPK fertiliser plus 150 kg ha⁻¹ AN fertiliser was applied. However, the interactions did not show a clear trend of how *N. brachypus* yield was responding to combinations of basal NPK application plus AN top-dressing fertiliser application with most of the treatment combinations, except the ones that attained the highest yield, producing tuber length, diameter and yield similar to the no fertiliser control. Therefore, more research is needed to understand the fertiliser requirements of *N. brachypus*, which like other wild RTCs, showed that it might require little or no fertiliser.

Keywords: Application rates, basal fertiliser, compound NPK fertilisers, in-row spacing, inter-row spacing, *Neorautanenia brachypus*, straight NPK fertiliser, tuber size, tuber yield

List of abbreviations

ADP – Adenosine Diphosphate

AMP - Adenosine Monophosphate

ANOVA – Analysis of Variance

ATP – Adenosine Triphosphate

AN – Ammonium Nitrate

AS – Ammonium Saltpeter

DAP – Diamonic Phosphate

DSP – Double Superphosphate

K – Potassium

LAD – Leaf Area Density

LAI – Leaf Area Index

MOP – Muriate of Potash

N – Nitrogen

NPK – Nitrogen, Potassium and Phosphorus

P – Phosphorus

PRISMA – Preferred Reporting Items for Systematic reviews and Meta-Analysis

RCBD – Randomised Complete Block Design

RTCs – Root and tuber crops

S.E.D – Standard Error of the Difference

sp. - Species

SOP – Sulphate of Potash

SP – Superphosphate

SSP – Single Superphosphate

TSP – Triple Superphosphate

WAE – Weeks after emergence

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CHAPTER 1: GENERAL INTRODUCTION

1.1 Background

Climate variability and change have been negatively affecting the diversity of crop-livestock systems that are a traditional livelihood strategy for the majority of smallholder farmers in semi-arid regions of southern Africa (Kahinda et al., 2007; Wani et al., 2009). Increased frequencies of drought and erratic rainfall pose major threats to natural processes that sustain fodder production for livestock and moisture for rain-fed crops (Tadross *et al.*, 2009). In terms of crop production, rising temperatures and precipitation variation have been reducing yields of many crops. This is because plant-soil-water relations are highly susceptible to these adverse weather conditions. According to Malhi et al. (2021), due to climate variability, pests and diseases have become more prevalent and as a result reducing crop yields. Increased temperatures are also associated with increased levels of heat stress to livestock that has a negative impact on feed intake, fertility, pregnancy outcomes, live-weight gain, and mortality (Marai et al., 2007).

To mitigate the effects of climate variability, farmers have adopted climate-resilient technologies such as bio-diversification, water harvesting and soil management practices (Malhi *et al.*, 2021). Furthermore, efforts to improve livestock feed have led to the cultivation of climate-resilient forage grasses and pasture legumes, such as *Chloris gayana*, *Cynodon nlemfuensis*, *Chamaecrista rotundifolia* and *Macroptilium atropurpureum*, in Zimbabwe (Mapiye *et al.*, 2006). Similarly, in the south-eastern lowveld of Zimbabwe, small-scale farmers have adopted an indigenous wild perennial tuber *Neorautanenia brachypus* (Harms) C.A. Sm. as a drought-relief feed for ruminant livestock (Pisa et al., 2022). This combination of climate-smart practices and crops helps farmers build resilience against the impacts of climate change.

The discovery of *N. brachypus* as livestock feed came from a farmer who observed his cattle eating unearthed tubers during ploughing (Murungweni et al., 2012). The farmer observed that the herd of cattle fed with the tuber survived severe drought and had better condition scores than those that were not fed the tuber (Nyarumbu *et al.*, 2019). Most of the cattle that did not receive the tuber as feed succumbed to drought and died (Murungweni *et al.*, 2012). After conducting feeding trials, Murungweni *et al.* (2012) concluded that *N. brachypus* contained adequate nutrients to meet the maintenance requirements of ruminant livestock (cattle and

goats) during a drought. Murungweni et al. (2014) asserted that *N. brachypus* has great potential in improving livestock production, including being used as a supplementary feed, an antibiotic, and a dewormer. These attributes of the tuber promoted its widespread adoption by many cattle owners. Besides nourishing the livestock with its nutrients, *N. brachypus* has the potential to deworm ruminant livestock of helminths (Mpofu et al., 2022).

Neorautanenia brachypus a leguminous perennial shrub belonging to the Leguminosae-Papilionaceae family, displays distinctive features. Its purple flowers give rise to dehiscent pods covered in dense hairs (Nyarumbu et al., 2019). Additionally, the plant forms an underground tuberous root, with tubers exhibiting various colours (brown, white, and cream) and texture (Hyde, 2014; Nyarumbu et al., 2019). Based on the leaf morphology of the plant and its genetic characteristics, different biotypes of *N. brachypus* have been discovered (Nyarumbu et al., 2019). Furthermore, propagation of *N. brachypus* is by both vegetative and seed, though the seeds require scarification before sowing because of a hard seed coat (Tauro et al., 2019). In terms of distribution, the tuberous plant is present in both previously cultivated areas and in the natural veld. Research conducted by Murungweni et al. (2012) revealed that the plant demonstrates adaptability to various soil types, with a higher frequency of occurrence observed in eutric vertisols and chromic luvisols.

As a leguminous plant, *N. brachypus* forms a symbiotic relationship with nitrogen-fixing bacteria of the *Pseudomonas* sp. (Kaseke, 2019). Additionally, *N. brachypus* has many beneficial traits because of its association with *Pseudomonas* sp. bacteria that including plant growth-promoting traits, including biological control activity and induction of system resistance to abiotic and biotic stress (Kaseke, 2019). The findings by Murungweni et al. (2012) also revealed that the average weight of *N. brachypus* tubers was 15 kg although they had potential to reach larger sizes of up to 45 kg. However, because *N. brachypus* produces subterranean tubers and is a perennial plant that loses its leaves during the cold dry season, there are no indicative above-ground plant characteristics that show the size of the tuber. Currently, there is no information on the size of individual tubers and total tuber yield per unit area, on a yearly basis, when the plant is growing in the wild or when planted as a crop using different spatial arrangements, populations, and fertiliser application regimes, in the quest to domesticate it.

Successful domestication of perennial plants requires improvement of propagation techniques and reducing the growth period (Mir-Makhamad et al., 2022). Additionally, optimising the

agronomic requirements of wild species of interest is another essential focus of domestication research (Mir-Makhamad *et al.*, 2022). Akinnifesi *et al.* (2007) assert that, to transit wild plants successfully into cultivation, directing attention at ensuring sufficient nutrient supply, promoting early physiological maturity, and addressing labour requirements for harvesting is key.

Sufficient nutrient supply is essential for plant growth and development, to maximise yield of domesticated plants. Nutrient deficiency and excessive supply could negatively affect plant growth and development, leading to a reduction in tuber quality and yield (Laboski & Kelling, 2007). In the case of *N. brachypus*, like other root and tuber plants, N is an essential nutrient for plant growth and plant vigour. The application of N during the early stages of plant growth increases the production of leaves and leaf expansion, resulting in enhanced leaf area index, duration, and improved radiation interception and production of photo-assimilates (Turamyenyirijuru, 2013). On the other hand, most tuber plants require a higher amount of K than N and P (Munyahali *et al.*, 2017; Oliveira *et al.*, 2022). This is because K is crucial for promoting the synthesis and translocation of assimilates to the tubers for starch synthesis (Turamyenyirijuru, 2013).

Recently, a few studies has been carried out to understand the agronomic requirements for *N. brachypus* production, starting from plant propagation to the application of P fertiliser. Tauro *et al.* (2019) showed that physical and acid scarification could break physical dormancy caused by hard seed coats in *N. brachypus* seeds. In addition, Pisa *et al.* (2022) found that the incremental addition of P fertiliser on ridges enhances tuber growth rate and reduces time to harvest for *N. brachypus*. This is because P is a key nutrient for root and tuber crops (RTCs), promoting early root and shoot development. It is also a component of energy molecules such as ATP, ADP, and AMP, thus, the addition of P in the cultivation of *N. brachypus* provides energy that is required for physiological processes in plants (Scheerer *et al.*, 2019). Therefore, optimising the application rates of N, P, and K fertilisers is crucial for successfully domesticating *N. brachypus* and enhancing its yield.

For maximising nutrient use efficiency in RTC, there is a need to optimise plant spacing and population density (Law-Ogbomo & Osaigbovo, 2014; Liu *et al.*, 2014). Plant spacing and population density are critical agronomic factors because they determine the availability of key resources such as nutrients, light, and water (Meena *et al.*, 2020). Narrow plant spacing and higher plant densities intensify competition for growth resources, leading to reduced growth

and lower yields (Muoneke et al. (2007). High plant densities also reduce space for vegetative growth and tuber development, this may result in mutual shading among leaves which reduces radiation interception and photosynthetic efficiency ((de Almeida et al., 2016; Masarirambi et al., 2012). Research shows that increasing plant spacing tends to enhance tuberous root yield per plant, as increased spacing reduces plant densities and competition for resources such as light, water, and nutrients (Meena et al., 2020). Contrarily, in potatoes,(Song et al., 2020; Tsedalu et al., 2014) discovered that high plant densities increase corm yield per unit area of land though it can reduce corm yield per individual plant.

On the other hand, when plants are widely spaced, resource use efficiency diminishes, as fewer plants occupy the available area, potentially reducing overall productivity Zaimoglu Onat et al. (2017). Meena et al. (2020) also discovered that at wider spacing there is low ground cover which can result in higher evaporation due to exposed soil, which results in moisture stress and reduced productivity. Also at low ground cover there is increased weed growth that will increase competition for growth resources thereby reducing productivity (Wees et al., 2016).

Optimal spacing ensures that each plant receives adequate nutrients, light, and water while minimising intraspecific and interspecific competition. As a result, adequate plant density ensures faster ground cover, enhancing radiation interception, improving photosynthesis and this in turn, can lead to greater yield potential. Therefore, domestication and commercial cultivation of *N. brachypus* require a comprehensive understanding of its optimal plant spacing and population density. By addressing these factors and effectively managing nutrient requirements, it is hypothesised that the successful cultivation and domestication of *N. brachypus* can be achieved with improved yield and resource use efficiency.

1.2 Statement of the problem

Ruminant livestock production in the lowveld area of Zimbabwe faces increasing challenges due to increased dry spells and erratic rainfall. In response, farmers have adopted *N. brachypus*, a wild leguminous plant, as a dry season feed (Murungweni *et al.*, 2012). The sufficient feed value of the *N. brachypus* tubers and medicinal properties have caused the plant to be of importance. Ideally, *N. brachypus* would be sustainably cultivated and harvested in sufficient quantities to meet the growing demand for livestock feed and medicinal products without risking the overexploitation of its natural populations. Currently, the plant only exists in the wild, making its commercial use to meet livestock feeding demands unsustainable (Pisa *et al.*,

2022). Furthermore, there is a risk of overexploitation of the natural genetic base of *N. brachypus* because of the unregulated harvesting of wild *N. brachypus* tubers (Pisa *et al.*, 2022). Additionally, because of its potential as a medicinal plant, public institutions like Chinhoyi University of Technology are currently researching the development of novel products from *N. brachypus* such as medicinal animal feeds, stress packs, anthelmintic drugs, wound healing drugs, antifungal drugs, and antibacterial drugs as part of its innovation hub projects. As this research progresses, the demand for *N. brachypus* tubers is expected to increase, further intensifying the strain on natural populations. Therefore, there is a need to domesticate *N. brachypus* and establish agronomic guidelines for its cultivation to ensure regular and sufficient supplies of the tuber for animal feed manufacturing and medicinal drug extraction industries that these research efforts may spawn. However, there is limited research on the agronomic recommendations for the domestication and commercial production of *N. brachypus*. Therefore, there is a need to evaluate the plant's fertiliser and plant spatial arrangement requirements to facilitate its domestication as a crop to produce enough tubers to satisfy research and future industrial requirements.

1.3 Justification

The increased occurrences of dry spells and unpredictable rainfall have led smallholder farmers to adopt *N. brachypus* as a drought survival feed, reducing livestock losses. The adoption of *N. brachypus* has increased through farmer-to-farmer extension resulting in a significant increase in demand for *N. brachypus*. In addition to its nutrient status as a feed, *N. brachypus* has anthelmintic effects when fed to ruminant animals. Furthermore, the demand has also increased because of ongoing research at Chinhoyi University of Technology that aims to develop novel products from *N. brachypus*, such as medicinal animal feeds and various medicinal drugs. However, the plant currently only exists in the wild, which makes commercial use unsustainable. Domestication offers a feasible solution for commercial production of the tuberous plant by farmers only if its plant spacing, population density, fertiliser requirements and adaptations to various agro-ecological regions in Zimbabwe are determined. Plants require optimal spacing and essential nutrients to support their growth, development and overall productivity. Plant spacing and population density are key factors that influence the availability of nutrients, light and water for plant growth and development (Law-Ogbomo & Osaigbovo, 2014; Liu *et al.*, 2014). However, no plant spacing and population density recommendations exist for *N. brachypus* production. By determining the optimal spacing and density,

competition among plants can be minimised, thereby improving nutrient uptake, photosynthesis, and overall biomass production for successful domestication and commercial cultivation. In root and tuber crop production plant spacing directly affects yield and resource use efficiency. Among the essential resources for growth, N, P, and K are the most common limiting macronutrients in root and tuber crop production (Tan *et al.*, 2016). Since no work has been reported on the N, P, and K requirements of *N. brachypus*, therefore, this study sought to determine the effects of N, P, and K-based fertilisers in *N. brachypus* cultivation. The use of inorganic NPK fertilisers has been widely adopted to enhance the production of domesticated plants. Balanced fertiliser application and optimum plant population density are key to achieving optimum growth and tuber yield for *N. brachypus*. By establishing the necessary plant spacing and fertiliser requirements, it will be possible to ensure sustainable production of *N. brachypus* tubers to meet the needs of research, development, and future industrial applications. This study will contribute information on the optimum plant spatial arrangement, population density, and mineral nutrient fertiliser recommendations for the growth and tuber yield of *N. brachypus* under smallholder farming conditions. This research output will facilitate the domestication of *N. brachypus* to ensure a regular and sufficient supply of tubers for animal feed manufacturing and medicinal drug extraction industries. The research and innovation towards the use of *N. brachypus* for animal feed manufacturing and the extraction of medicinal phytochemicals are aligned with the objectives Education 5.0 and the new Zimbabwe National Industrial Development Policy 2024-2030 of accelerating transition from a primary commodity-based economy towards a technologically advanced and diversified industry and commerce by 2030. A key tenet of these complementary policies is for the government to facilitate research and development in research and innovation institutions in Zimbabwe, including universities, in the processing and value-addition locally available products, such as *N. brachypus*, and the commercialization of intellectual property therefrom, to expand and diversify the countries industrial base (ZMIC, 2019).

1.4 Objectives

1.4.1 Main objective

The main objective of the research project was to determine the plant spatial arrangement, plant population, and mineral nutrient requirements of *N. brachypus* to facilitate its domestication as a commercial crop.

1.4.2 Specific objectives

- 1 To review the effects of inorganic N, P, and K fertilisers on the growth and yield of root and tuber crops across various geographical regions and environmental conditions.
- 2 To determine the effect of plant spatial arrangement and population density on the growth and tuber yield of *N. brachypus* in the first two years after planting in two contrasting agroecologies.
- 3 To determine the effects of N, P, and K mineral nutrients, their combinations as straight fertilisers, and application rates of NPK and N-top dressing fertilisers on the growth and tuber yield of *N. brachypus* in the first two growing seasons in two contrasting agroecologies.

1.5 Hypotheses

H₀: Types and application rates of inorganic NPK fertilisers have no significant effect on the growth and yield of root and tuber crops (RTCs) across various geographical regions and environmental conditions.

H₀: Plant spatial arrangement and population density have no significant effect on the growth and tuber yield of *N. brachypus* in the first two years after planting in two contrasting agroecologies.

H₀: N, P and K mineral nutrients and their combinations, as well as NPK and N-top dressing fertiliser application rates, have no significant effect on the growth and tuber yield of *N. brachypus* during the first two growing seasons in two contrasting agroecologies.

1.6 Outline of the dissertation

The dissertation consists of five complementary chapters. Chapter 1 introduces *N. brachypus* and its growing importance as a dry season feed that is used to mitigate the effects of severe droughts on ruminant production in the south-eastern lowveld region of Zimbabwe. The chapter establishes the background and rationale for the study and states the research objectives. Chapter 2 is a systematic review of the current state of knowledge on the effect of individual N, P, and K mineral nutrients and their combinations as straight and compound fertilisers on the growth and yield of root and tuber crops. The observations from this review indicate that plant population density influences the effectiveness of mineral nutrient application. This prompted the evaluation of the effects of plant spatial arrangement and

population densities on tuber size and yield of *N. brachypus* in Chapter 3. Chapter 2 also provided background information for Chapter 4, in which the results of experiments on the effect of NPK fertilisers on *N. brachypus* growth and yield were described and put into context with the general state of knowledge on the effect of NPK fertilisers on root and tuber crops. All the research findings were extensively discussed in Chapter 5, and conclusions regarding the optimum plant spatial arrangement and fertiliser requirements for *N. brachypus* tuber growth were derived to provide valuable insights for its domestication and cultivation.

CHAPTER 2: Effect of nitrogen, potassium, and phosphorus inorganic fertilisers on growth and yield of root and tuber crops: A systematic review

Abstract

Production and consumption of root and tuber crops (RTCs), compared to many staples in semi-arid regions, have extensively increased. While studies have investigated different methods of mineral nutrient management and their impact on RTCs cropping systems, the findings are inconsistent and fail to provide a comprehensive understanding of the subject. Therefore, a systematic literature review has been used to examine the impact of inorganic nitrogen (N), potassium (K), and phosphorus (P) fertilisers on the growth and yield of widely cultivated RTCs. To map the existing research on the application of inorganic fertilisers to RTCs, the Preferred Reporting Items for Systematic reviews and Meta-Analysis methodology was used. The search was limited to research articles published in English between 2010 and 2022. Articles published as review papers, book chapters, and conference papers were excluded. A total of 34 papers were reviewed that met the inclusion criteria, and these resulted in 310 observations. The review indicated the importance of N as a plant growth-promoting macronutrient, P as an essential nutrient for energy-requiring physiological activities, and K as a macronutrient that activates metabolic reactions. The reviewed papers showed that RTCs have variable responses to increases in N, P, and K application rates, and have different optimum application rates. Optimal nutrient requirements varied within plant species and by plant species, and excessive application potentially led to reduced tuber yield and quality. In conclusion, the review showed variable responses ranging from positive to negative responses to the application of NPK fertilisers for tropical RTCs such as sweet potato and cassava, while for potato yield generally increased with the application rate of NPK, up to an optimum application rate, and were maintained or decreased at higher application rates. The variation in fertiliser responses, both within and across RTC species, highlights the need for site-specific and species-specific fertiliser recommendations.

Keywords:

Application rate; Inorganic fertiliser; Macronutrients; Systematic review; Tuber yield

1.1 Introduction

Root and tuber crops (RTC) are plants that develop fleshy underground starchy storage structures that are important for human consumption, animal feed, pharmaceuticals, and industrial use (Chandrasekara & Josheph Kumar, 2016; Kumar *et al.*, 2016; Mpofu *et al.*, 2022; Sanginga, 2015). Starch occurs in plant tissues as starch grains and is composed of two polysaccharides, amylose and amylopectin (Bertoft, 2017; Zabala, 2020). RTCs store starch in different morphological storage structures, such as rhizomes, corms, stems, and roots, depending on the species (FAO, 2021). Based on their morphological storage structure, RTCs can be classified into several categories: stem tubers, such as potato (*Solanum tuberosum* L.) and Jerusalem artichokes (*Helianthus tuberosus* L.); tuberous roots, including cassava (*Manihot esculenta* Crantz), *N. brachypus*, and sweet potato (*Ipomoea batatas* (L.) Lam); rhizomes, such as ginger (*Zingiber officinale* Roscoe); corms, including taro (*Colocasia* spp.); and taproots, such as yam (*Dioscorea* spp.) and carrot (*Daucus carota* L.) (Zhang *et al.*, 2023; Zierer *et al.*, 2021). According to Palaniswami and Peter (2008), RTCs can also be classified into major RTCs or minor RTCs. Major RTCs include potato, cassava, sweet potato, yams, taro, cocoyam (*Xanthosoma* spp.), and tannia (*Xanthosoma sagittifolium* (L.) Schott.) (Palaniswami & Peter, 2008; Tay, 2012). Minor RTCs include Jerusalem artichoke, arrow root (*Maranta arundinacea* L.), winged bean (*Psophocarpus tetragonolobus* (L.) DC.), yam bean (*Pachyrhizus tuberosus* (Lam.) Spreng.), canna (*Canna indica* L.), and safed musli (*Chlorophytum borivilianum* Sant. and Fernand.), just to mention a few (Palaniswami & Peter, 2008; Tay, 2012).

RTCs contribute significantly to global food production as a major source of carbohydrates, second only to cereals (Chandrasekara & Josheph Kumar, 2016). With respect to global food security, RTCs contribute 5.4% of human energy for average consumption (Nanbol & Namo, 2019; Nayar, 2014). Compared to many staples in semi-arid regions, they produce high yields per land unit and per unit of time (Dhliwayo, 2002; Liu *et al.*, 2014). This has been evident with their annual global production of approximately 861 million tonnes on approximately 64 million hectares of land (FAO, 2021). Potato, cassava, sweet potato, and yams are the most cultivated RTCs in the world (FAO, 2021; Liu *et al.*, 2014). In terms of production, among the RTCs, potato are the most important, with the highest protein-to-calorie ratio and an annual global production of 376 million tonnes (Mu & Li, 2019; Nayar, 2014). Second to potato is cassava, which has an annual global production of 276 million tonnes (FAO, 2021; Sanginga,

2015). Ranking third are sweet potato, with an annual global production of 105 million tonnes (Mu & Li, 2019). Similar to cassava, a greater percentage (95%) of the global production of sweet potato is in developing countries. Furthermore, cassava, sweet potato, and yams constitute the major famine reserve as rural food staples, contributing more than 40% of all the calories that are consumed in sub-Saharan Africa (Chen et al., 2022; Nanbol & Namo, 2019).

As a famine reserve, RTCs have high nutritional value compared to other staple crops. These crops are of great importance because of their starch and non-starch carbohydrates compositions (Tonukari, 2004). Among the starchy staples, cassava and yams, with a carbohydrate composition of 35% and 33% (respectively) provide about 40% more calories to human nutrition and animal diet than rice and about 25% higher than maize (Tonukari, 2004). In addition to their carbohydrate content, RTCs have other nutrients that are important to human and animal nutrition. They have fibre ranging from 0.6-2% depending on the crop species, with cassava and tannia having the highest fibre content (Aliou, 1998; Tonukari, 2004). The ash content of these RTCs ranges from 0.6 to 1.4%, indicating the presence of minerals and inorganics such as magnesium and calcium (Aliou, 1998). They also have a significant protein composition that ranges from 1.0-3.7%, and fat composition ranges from 0.16-6.4% (Tonukari, 2004). Furthermore, RTCs have also other metabolites that provide important nutritional benefits, such as amino acids, carotenoids, and phenolic compounds such as carotene, thiamine, ascorbic acid, riboflavin, xanthophylls, anthocyanins, and acetate (Aliou, 1998; do Prado Aparecido et al., 2022; Liu et al., 2014). These other metabolites are richly found in sweet potato, and potato. The presence of these and other several nutraceutical components, such as vitamin A, vitamin C, phenolic acids, and amino acids has resulted in increased recognition of sweet potato in diabetic patients' diets (Liu *et al.*, 2014).

Despite the importance and wide adoption of RTCs, achieving attainable root and tuber yields remains a significant challenge in the smallholder farming sector. This is because the production of RTCs is being curtailed by several abiotic, biotic and socioeconomic factors such as pests and diseases, inaccessibility to improved varieties and planting materials, variability in water supply and lack of capital (Abrham et al., 2021; Liu et al., 2014). Among many other reasons, soil fertility management is also a key contributor to the yield gap. This is because the production of RTCs, except potato, is mainly done on marginalised land without supplementing the soil's nutrients (Chandrasekara & Josheph Kumar, 2016; Koostanto et al., 2016). These RTCs, except for potato, are adaptable to marginal soils and are tolerant of a wide range of

edaphic and climatic conditions (Chandrasekara & Josheph Kumar, 2016; Tonukari, 2004). Therefore, many smallholder farmers have been cultivating these without replenishment of mineral nutrients. This continuous cropping without fertilisers has resulted in declining soil structure and fertility, causing a noticeable decline in RTCs yield since 2010 (FAO, 2023; Sanginga, 2015). The FAO records showed that the area under production and harvest for RTCs in Africa increased by 9.89% from 2018 to 2021, but the yield declined from 9.13 t ha⁻¹ in 2018 to 8.58 t ha⁻¹ in 2021 (FAO, 2023). Global production also showed a decline in yield from 13.78 t ha⁻¹ in 2018 to 13.19 t ha⁻¹ in 2021, despite a 6.77% increase in land under production (FAO, 2023).

Mineral nutrient replenishment plays an important role in RTC production for high attainable yields and the production of good-quality tubers (Bhardwaj et al., 2021). In addition, mineral nutrient management is essential in reducing the effects of pests and diseases hence increasing RTCs yield. For example, acid-forming fertilisers such as sulphur-containing fertilisers are essential in controlling common scab (Liu *et al.*, 2014). Notably, mineral nutrient requirements are different depending on several variables such as RTC species, variety, soil moisture content, soil type, soil pH levels and climatic conditions of the area. For example, potato need optimal levels of essential nutrients throughout the growing season to ensure normal plant growth and tuber development (Liu *et al.*, 2014). However, in cassava production, basal fertiliser is key and the application of K fertiliser in the later period of the plant's growth is important for increasing root and top biomass. This is also true with sweet potato, which requires a significant amount of K at the tuber bulking stage to favour the thickening of storage roots (Howeler, 2001; Liu *et al.*, 2014).

While several studies have investigated different methods of mineral nutrient management and their impact on RTC cropping systems, the findings always lack consistency and fail to provide a comprehensive understanding of the subject. Neina (2021) suggested the establishment of a special fertiliser management program that is specific to the needs of RTCs, for example, by aiming for more K fertiliser for yam production. Whereas, Duque and Villordon (2019) emphasized the optimisation of nutrient supply to enhance tuber yield and economic returns in these RTCs. Moreover, Wang et al. (2022) recommended against excessive use of chemical fertilisers to decrease potential environmental problems. Other researchers have given blanket recommendations without the basis of soil type, initial soil fertility or the variety of the plant. For example, Liu *et al.* (2014) recommended the application of approximately 220–270 kg N

ha⁻¹, 28–40 kg P ha⁻¹, and 310–360 kg K ha⁻¹ for the production of potato plants. Therefore, by conducting a comprehensive literature review, the available information can be synthesized and the strengths and limitations of previous studies can be analysed. A systematic literature review is, therefore, necessary to bridge this knowledge gap and provide a comprehensive synthesis of the existing research. This will help identify trends, patterns and inconsistencies in existing findings on the effects of macro-nutrients (NPK) and NPK fertilisers on RTC growth and yield under different climatic and agronomic conditions. The objective of this systematic literature review was, therefore, to determine the specific effects of different types and application rates of inorganic NPK fertilisers on the growth and yield of RTCs in various geographical regions and environmental conditions. The following research questions were formulated: a) What is the effect of macro-nutrients NPK and their combinations on the growth and yield of RTCs? (b) What is the effect of the application rate of NPK compound fertilisers on the growth and yield of RTCs? (c) What are the NPK fertiliser recommendations for RTCs?

2.2 Materials and methods

2.2.1 Search strategy

For this systematic literature review, an online search strategy was developed to identify relevant literature. The search strategy was tailored to three databases: Scopus, Web of Science, and Dimensions. The search included peer-reviewed research articles published from 2010 to 2022 in English only, without limits on geographical location or climatic region. Searches on databases were conducted from the 7th of May 2022 to the 11th of December 2022. The following search strings were created from the topic key words combined with different Boolean operators: (inorganic nitrogen OR phosphorus OR potassium AND ‘root yield’ AND ‘tuber yield’), (inorganic AND (nitrogen OR phosphorus OR potassium) AND ‘root growth’ AND ‘tuber yield’), (inorganic AND NPK AND (fertiliser OR fertiliser) AND ‘tuber yield’ AND ‘root yield’), (inorganic AND NPK AND (fertiliser OR fertiliser) AND ‘tuber growth’), (inorganic (fertiliser OR fertiliser) AND root AND tuber AND yield), ((fertiliser OR fertiliser) AND root AND tuber AND growth AND yield).

The search mainly focused on mapping the existing literature on the effect of N, P, and K-based inorganic fertilisers on root and tuber crop yield. The search was limited to the fields of agricultural and biological sciences and environmental science. Furthermore, it was then narrowed down to soil science, plant science, and agronomy. The search focused on field experiments only; pot and controlled experiments were excluded. Only original research

articles were included; review papers and conference papers were excluded. For quality maintenance, all duplications were thoroughly checked and deleted. Abstracts of articles were read and thoroughly checked to ensure the quality and relevance of the literature included in the review process. The schematic representation of the screening process is given in Figure 2.1. In the data extraction phase, 34 articles were subsequently selected and analysed to provide 310 observations, and the characteristics of the extracted papers were:

- 1) The article must be an original research paper, not a review paper, conference paper, published report, or case study.
- 2) The article must be in English and from the fields of agricultural, environmental, and biological sciences.
- 3) The articles must be published between 2010 and 2022.
- 4) The extracted papers were from rain-fed field experiments only.

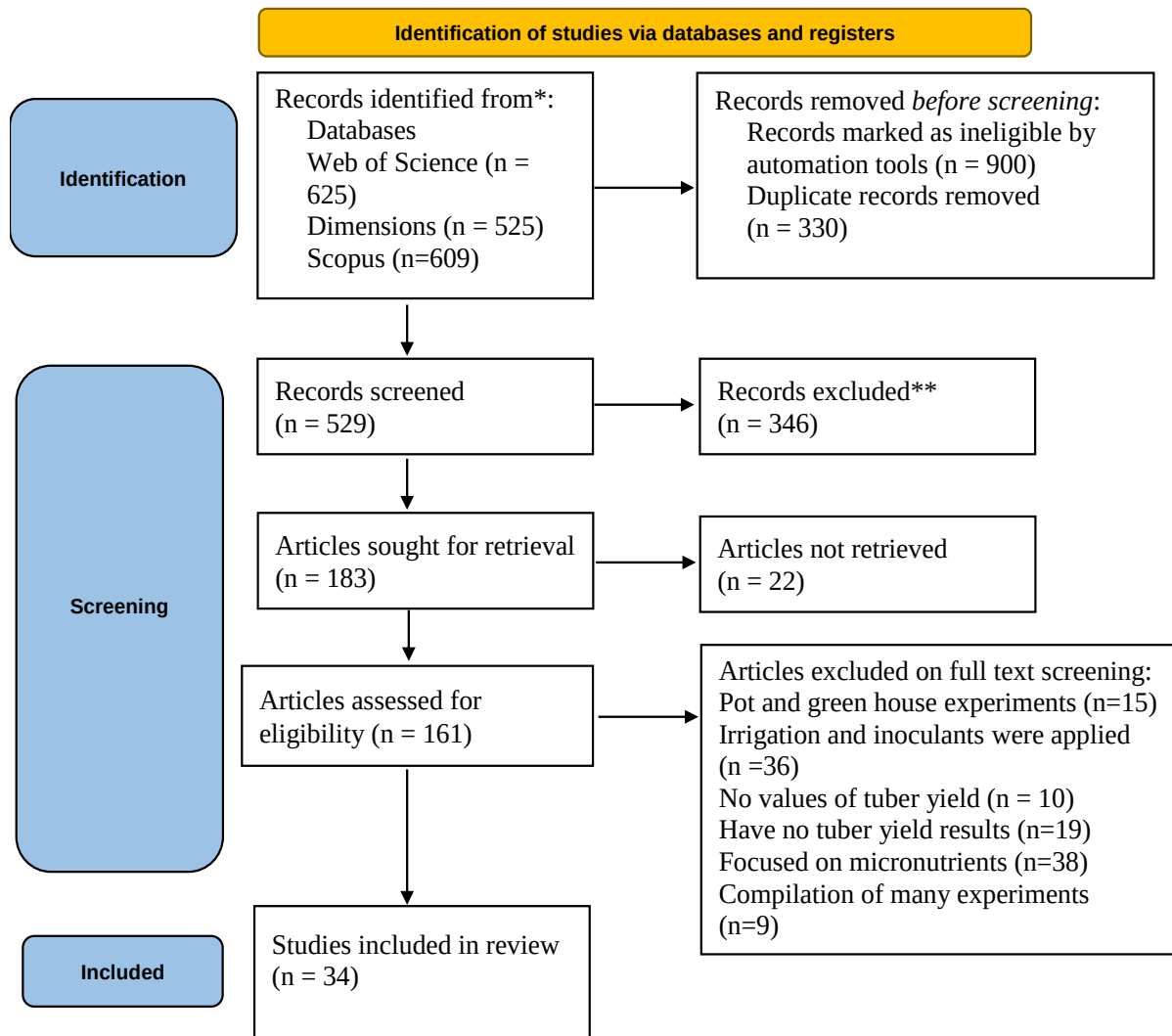


Figure 2.1: Literature inclusion and exclusion criteria at every stage of the PRISMA Statement by (Preferred Reporting Items for Systematic reviews and Meta-Analysis).

2.2.2 Basic properties of data set

The analysis of the effects of N, P, and K on the growth and yield of RTCs was categorised into five different criteria. The criteria are: 1) the impact of N fertiliser application rates; 2) the impact of P fertiliser application rates; 3) the impact of K fertiliser application rates; 4) the impact of applying different combinations of individual macronutrients as straight fertilisers (NP, NK, PK, and NPK); and 5) the impact of compound NPK fertiliser application rates on RTC growth and yield. Then the experimental data was extracted from each paper, including location, climatic conditions, experimental design, and yield. Each experimental treatment was considered an individual observation.

2.2.3 Risk of bias analysis and the limitations of the study

The Cochrane Collaboration's risk of bias assessment criteria were used to determine the risk of bias and variability for this systematic literature review (Sterne *et al.*, 2019). The five domains used were rated according to Cochrane's Risk-of-bias visualization tool requirements. The included studies were classified as being at overall risk of bias using all five domains: bias arising from the randomisation process; bias due to deviations from the intended intervention; bias due to missing outcome data; bias in the measurement of the outcome; and bias in the selection of the reported result. For a study to be judged to have an overall low risk of bias, it should have a low risk of bias in all five domains. For a study to be judged as having some concerns, it should have at least one concern amongst the five domains and with no domain at high risk of bias. Lastly, for a study to be judged to have an overall high risk of bias, it should have at least one domain with a high risk of bias. The Risk-of-bias visualization tool (Robvis) was used to present the summary plot for the risk-of-bias assessment.

2.3 Results

2.3.1 Geographical distribution of observations

Our screening process reveals that accessible, published papers of a high reporting standard suitable for this systematic literature review were concentrated in Asia (43% of the observations), particularly in China (12% of the observations) (Table 2.1). The accessible studies were reported from 16 countries. In the following text, numbers in brackets indicate the number of individual observations in the categories described. Together with China, Poland (n = 42), Ethiopia (n = 41), India (n = 32), and Brazil (n = 31) were countries with the highest frequency of studies on the effect of inorganic NPK mineral nutrients and fertilisers on RTC growth and yield.

Table 2.1: List of studies included in the systematic literature review, with study area and number of extracted observations.

Continent	Country	Number of observations	Studied plant	Reference
Africa	Nigeria	10	Sweet potato	Aboyeji <i>et al.</i> 2019
Africa	Ethiopia	12	Potato	Gelaye <i>et al.</i> 2022
Africa	Ethiopia	4	Potato	Getahun <i>et al.</i> 2019
Africa	Ethiopia	11	Potato	Haile and Boke, 2011
Africa	Uganda	8	Cassava	Katuromunda <i>et al.</i> 2021
Africa	Mozambique	9	Sweet potato	Munda <i>et al.</i> 2019
Africa	Democratic Republic of Congo	12	Cassava	Munyahali <i>et al.</i> 2017
Africa	Zambia	6	Cassava	Mwamba <i>et al.</i> 2021
Africa	Ethiopia	10	Potato	Setu and Mitiku, 2019
Africa	Ethiopia	4	Beetroot	Sinta and Garo, 2021
Africa	Nigeria	8	Cassava	Uwah <i>et al.</i> 2013
Asia	China	12	Sweet potato	Duan <i>et al.</i> 2018
Asia	China	3	Sweet potato	Duan <i>et al.</i> 2019
Asia	Pakistan	21	Potato	Khan <i>et al.</i> 2010
Asia	India	4	Potato	Manorama <i>et al.</i> 2017
Asia	India	15	Potato	Mozumder <i>et al.</i> 2014
Asia	Bangladesh	22	Aquatic taro	Noor <i>et al.</i> 2013
Asia	Kazakhstan	12	Potato	Nurmanov <i>et al.</i> 2019
Asia	India	8	Potato	Sandhu <i>et al.</i> 2013
Asia	Indonesia	9	Taro	Suminarti <i>et al.</i> , 2022
Asia	China	18	Potato	Tan <i>et al.</i> 2016
Asia	China	4	Sweet potato	Wang <i>et al.</i> 2014

Asia	India	5	Potato	Yadav <i>et al.</i> 2022
Europe	Poland	5	Potato	Grzebisz <i>et al.</i> 2018
Europe	Poland	6	Potato	Grzebisz <i>et al.</i> 2020
Europe	Poland	4	Potato	Kołodziejczyk, 2014
Europe	Poland	27	Jerusalem artichoke	Wierzbowska <i>et al.</i> 2021
Europe	Russia	4	Potato	Yakimenko and Naumova, <i>et al.</i> 2021
North America	Canada	6	Potato	Zebarth <i>et al.</i> 2011
South America	Brazil	5	Cassava	Gonçalves <i>et al.</i> 2021
South America	Brazil	5	Sweet potato	Luz <i>et al.</i> 2013
South America	Brazil	5	Cassava	Mota <i>et al.</i> 2019
South America	Brazil	8	Potato	Santos <i>et al.</i> 2018
South America	Brazil	8	Potato	Yagi <i>et al.</i> 2019

The most commonly studied climate zones were Aw (n = 86) a tropical savanna, Cfb (n = 50) and Cwa (n = 47) a warm temperate with a dry winter and a hot summer, with the most frequent research being on potato and sweet potato for all the climate zones (Table 2.2). Furthermore, potato was widely studied across all climatic zones except for Af a tropical rainforest, fully humid climate and Am a tropical monsoon climate (Table 2.2).

Table 2.2: Summary of evaluated plant types as per Koppen-Geiger climate zone.

Botanical name	Climate type									
	Af	Am	Aw	Bsh	Bsk	Cfa	Cfb	Cwa	Cwb	Dfb

<i>Beta vulgaris</i> L. (beet root)					4									
<i>Colocasia esculenta</i> L. (aquatic taro)					22									
<i>Helianthus tuberosus</i> L. (Jerusalem artichoke)										27				
<i>Ipomoea batatas</i> (L.) Lam (sweet potato)					19					4			15	5
<i>Manihot esculenta</i> Crantz (cassava)					8					13			11	12
<i>Solanum tuberosum</i> L. (potato)					41	13	30	8	23	21	15	10		
<i>Xanthosoma sagittifolium</i> (L.) Schott. (Mbothe taro)					9									
Total number of observations	8	22	86	13	30	12	50	47	32	10				

Note Af – Tropical rainforest, Am = Tropical monsoon, Aw = Tropical savanna, Bsh = Hot semi-arid, Bsk = Cold semi-arid, Cfa = Humid subtropical, Cfb = Temperate oceanic, Cwa = Warm temperate with dry winter, Cwb = Temperate highland with dry winter, Dfb = Warm-summer humid continental.

2.3.2 Observed plant, soil, and fertiliser types

The most studied plant was potato (n = 161) with 13 varieties; cassava (n = 44) with eight identified varieties; and sweet potato (n = 43) with four identified varieties (Figures 2.2 and 2.3).

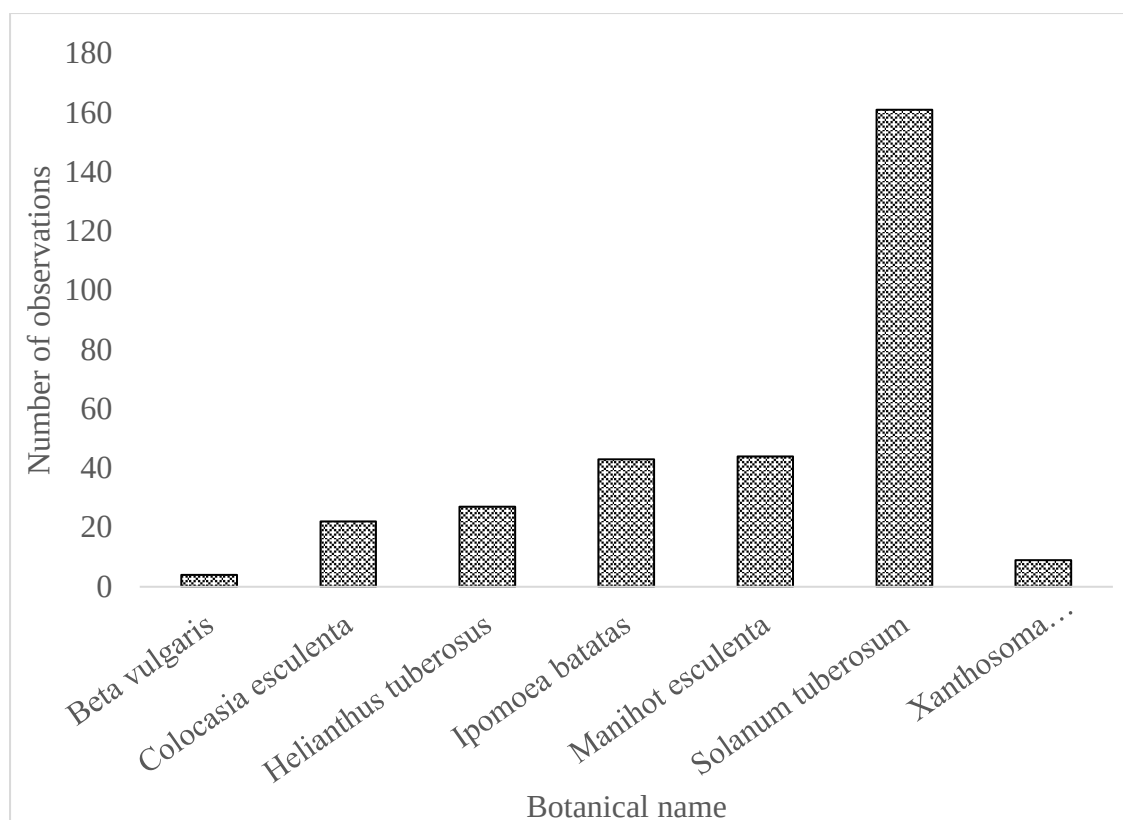


Figure 2.2: Summary chart showing number of observations included in the systematic review for each RTC.

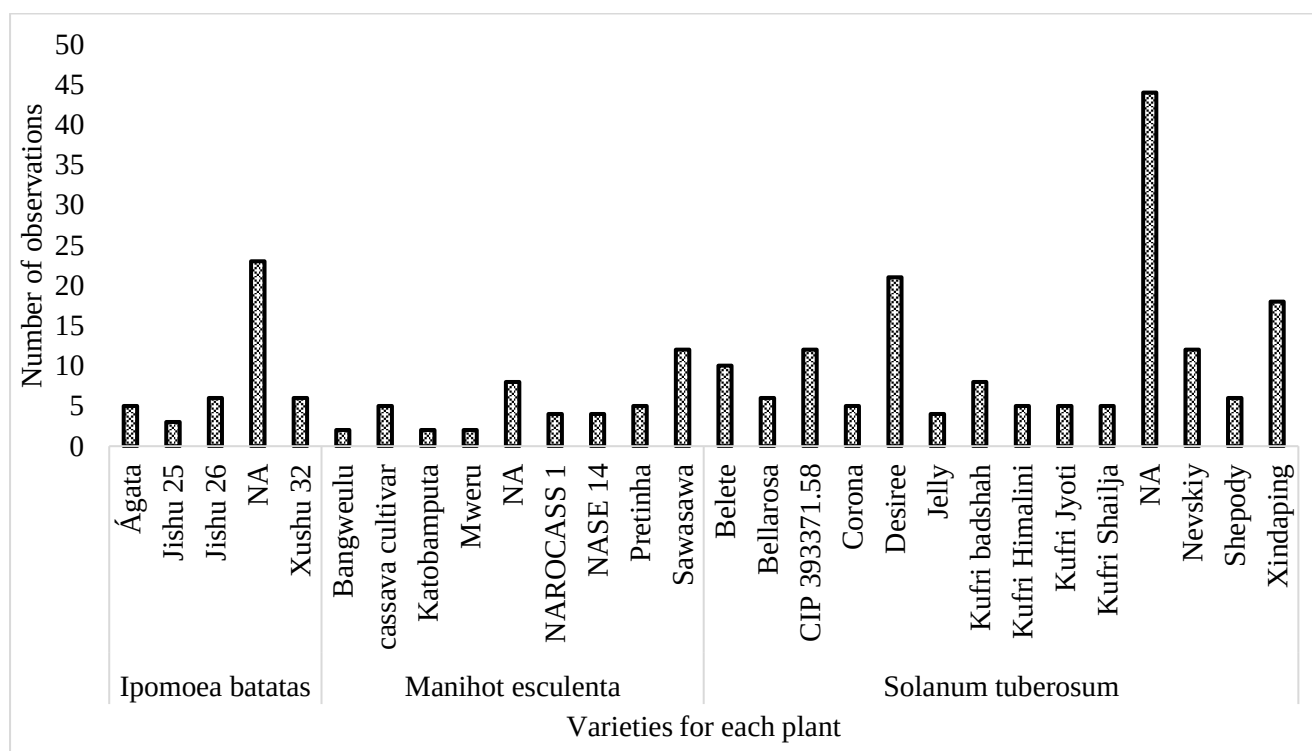


Figure 2.3: Summary of identified varieties evaluated for the most cited plants.

Most studies were carried out on sandy loam soils (42% of the observations) and loam soils (25% of the observations), with the least number of studies, approximately 1%, being carried out on silty soil (Figure 2.4a). A total of 113 from the 310 observations were carried out on acidic soils ranging from a pH value of 5.5 to 6.5. For N, P, and K mineral nutrient supply, urea (67%), TSP (37%), and MOP (53%) were the most commonly used fertiliser types, respectively (Figures 2.4b, 2.5a, and 2.5b).

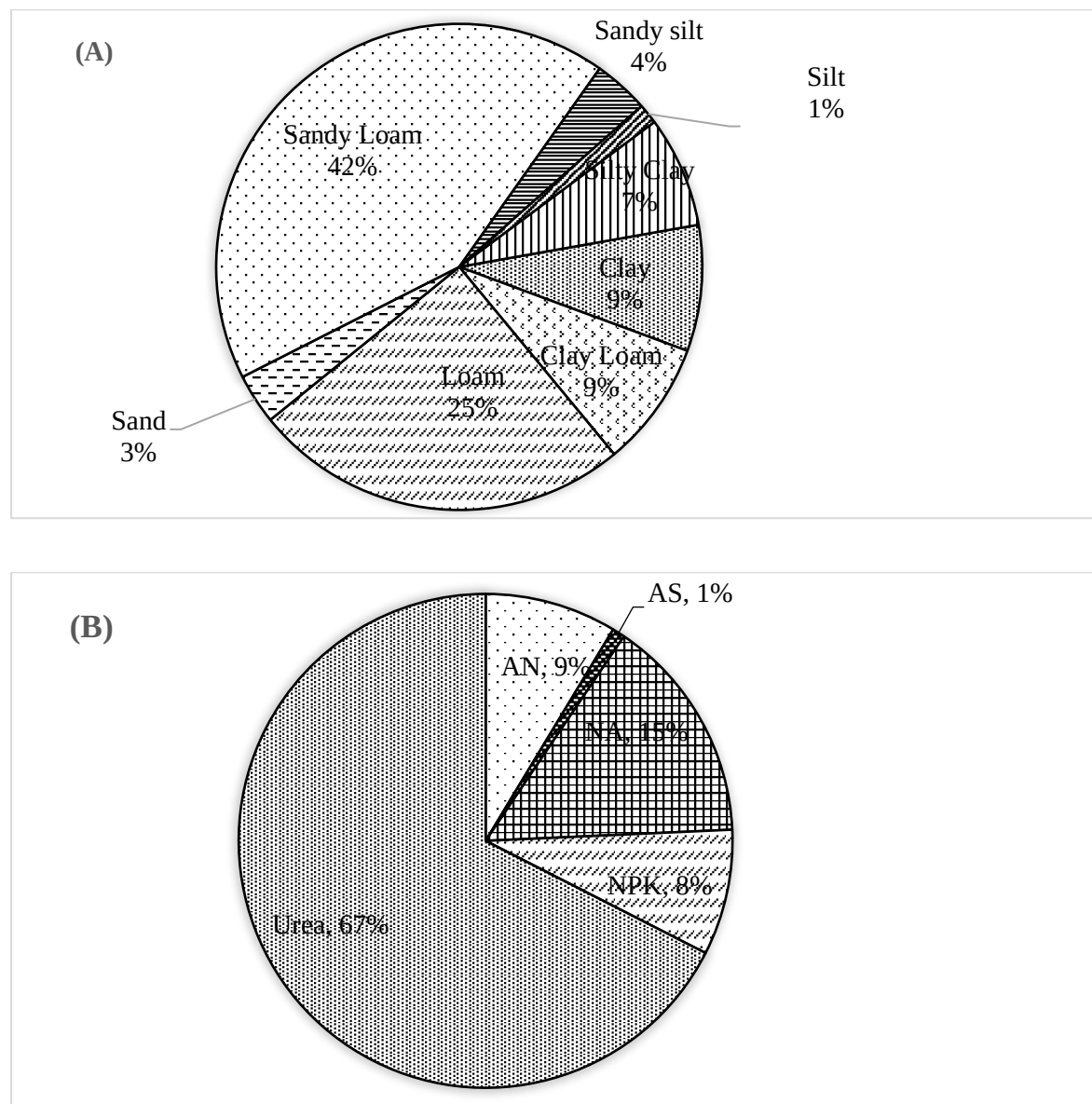


Figure 2.4: Pie charts to show (a) percentage of studies carried out on different soil types (b) proportion of different sources of N-based fertilisers used in assessed studies

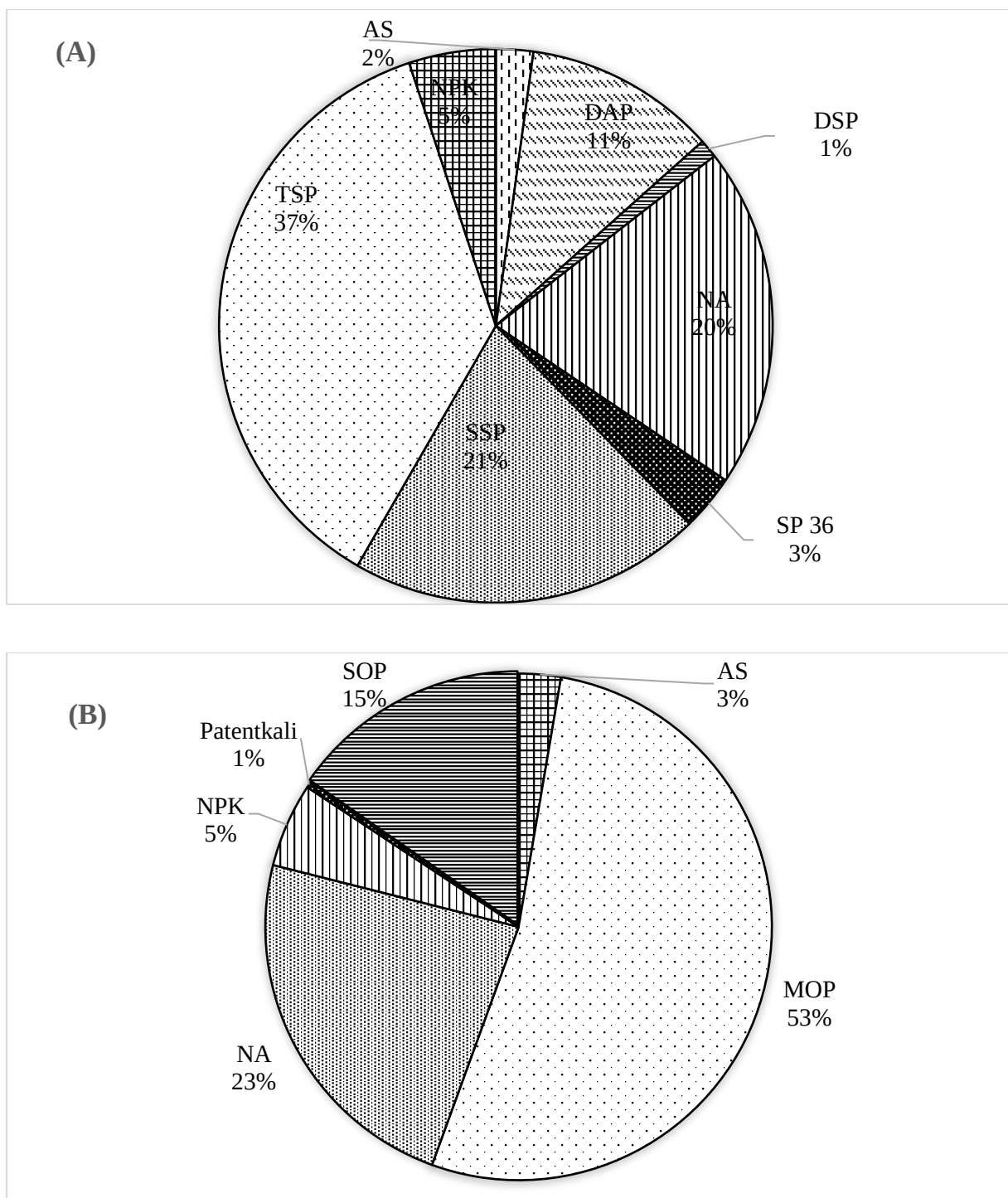


Figure 2.5: Pie charts showing proportion of different sources of (a) P-based fertilisers and (b) K-based fertilisers used in assessed studies

Most studies had fertiliser treatments applied as a basal application using plough sole (n = 75) as the method of application. The other most commonly used methods were band application (n = 44) and side dressing (n = 21) (Figure 2.6).

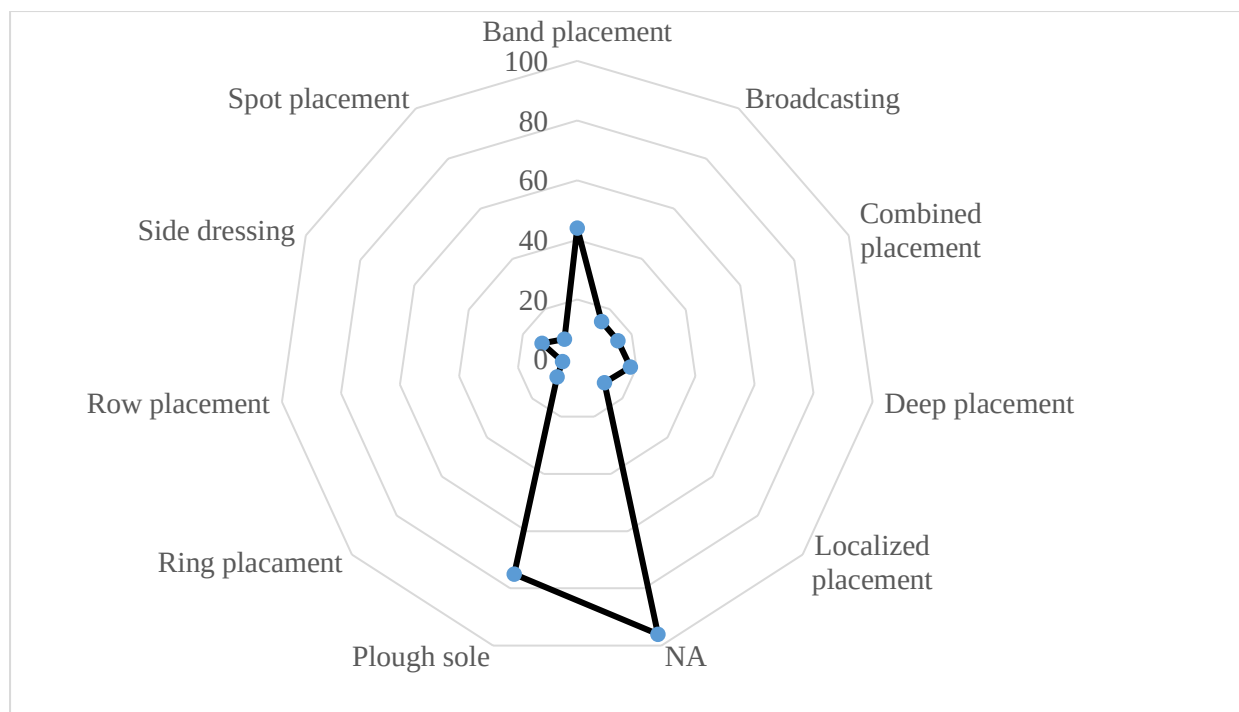


Figure 2.6: Fertiliser application methods that were used in reviewed studies.

2.3.3 Impacts of inorganic fertilisers on yield and yield components of root and tuber crops

A greater number of the studies assessed the effect of N fertiliser application rates on tuber production (n = 97). Sixty-nine (69) of the 310 observations evaluated the effects of K fertiliser application rates and 84 evaluated the response of RTCs to the application of different combinations of N, P & K. In the assessed studies five different yield parameters were observed (Table 2.3) that were investigated and found to be affected by fertiliser application. These were tuber yield (mentioned in 94% of the publications), number of tubers per plant (51%), tuber length (17%), tuber weight (49%), and tuber diameter (14%). Other publications also focused on the growth analysis parameters of the plants that are affected by inorganic fertilisers. These include plant height (mentioned in 29% of the publications), total dry matter content (43%), number of leaves (23%), stem number (20%), and marketable yield (23%). Other publications looked further into the nutrient composition after application of different fertilisers; this included tuber proximate analysis (23%), and the nutrient composition of leaves (29%).

Table 2.3: Summary of inorganic fertiliser application rates impacts on RTCs growth and yield from reviewed publications.

Root and Tuber crop	Fertiliser type and application rates	Tuber yield responses	Yield component responses (weight, number, length and diameter)	References
Sweet potato	Urea (46.4% N) at 0, 120, & 240 kg ha ⁻¹	Negative response: Tuber yield reduced with application of 120 kg of urea/ha and further reduced with application of 240 kg ha ⁻¹	Negative response: Tuber weight and tuber number reduced with application of 240 kg of urea/ha	Duan <i>et al.</i> 2018
Sweet potato	Urea (46.4% N) at 0, 75, & 150 kg ha ⁻¹	Quadratic response: Tuber yield increased up to 75 kg of urea/ha and decreased with application of 150 kg ha ⁻¹	Sigmoidal response: Tuber weight increased with application of 75 kg of urea/ha and was similar at 150 kg ha ⁻¹ Negative response: Tuber number reduced with application of 75 kg of urea/ha and of 150 kg ha ⁻¹ urea	Duan <i>et al.</i> 2019
Sweet potato	MOP (50% K ₂ O) at 0, 40, 80, 120, & 160 kg ha ⁻¹	Quadratic response: Tuber yield increased up to 80 kg MOP/ha and slightly	Not recorded	Aboyaji <i>et al.</i> 2019

		decreased at 120 kg ha ⁻¹ and 160 kg ha ⁻¹		
Sweet potato	SOP (50% K ₂ O) at 0, 150, 300, & 450 kg ha ⁻¹	Sigmoidal response: Tuber yield increased up to 300 kg SOP/ha and was similar at 450 kg ha ⁻¹	Sigmoidal response: Tuber weight increased up to 150 kg SOP/ha and was similar at 300 kg ha ⁻¹ and 450 kg ha ⁻¹	Wang <i>et al.</i> 2014
			Positive response: Tuber number increased up to 450 kg SOP/ha	
Sweet potato	SSP (17%P ₂ O ₅) at 0, 20, & 40 kg ha ⁻¹	Sigmoidal response: Tuber yield increased up to 20 kg SSP/ha and was similar at 40 kg ha ⁻¹	Not recorded	Munda <i>et al.</i> 2019
Sweet potato	SSP (17% P ₂ O ₅) at 0, 200, 400, 600, & 800 kg ha ⁻¹	Sigmoidal response: Tuber yield increased up to 600 kg SSP/ha and was similar at 800 kg ha ⁻¹	Not recorded	Luz <i>et al.</i> 2013
Cassava	Urea (46% N) at 0, 50, 100, 150, & 200 kg ha ⁻¹	Sigmoidal response: Tuber yield increased up to 50 kg urea/ha and was similar up to 200 kg ha ⁻¹	Positive response: Tuber number increased up to 200 kg urea/ha No response: Tuber length and diameter did not respond to fertiliser application	Mota <i>et al.</i> 2020

Cassava	SOP (50% K ₂ O) at 0, 30, 60, 90, & 120 kg ha ⁻¹	Quadratic response: Tuber yield increased up to 60 kg SOP/ha and slightly decreased at 90 kg ha ⁻¹ and 120 kg ha ⁻¹	Quadratic response: Tuber number increased up to 60 kg SOP/ha and slightly decreased at 90 kg ha ⁻¹ and 120 kg ha ⁻¹ Quadratic response: Tuber diameter increased up to 60 kg SOP/ha and slightly decreased at 90 kg ha ⁻¹ and was similar at 120 kg ha ⁻¹	Gonçalves <i>et al.</i> 2021
Cassava	Urea (46.4% N) at 0, 40, 80, & 120 kg ha ⁻¹	No response: Tuber yield did not respond to fertiliser application	No response: Tuber length did not respond to fertiliser application	Uwah <i>et al.</i> 2013
	MOP (50% K ₂ O) at 0, 40, 80, & 120 kg ha ⁻¹ (NK)			
Cassava	Compound NPK (17N ⁻¹ 7P ₂ O ₅ ⁻¹ 7K ₂ O) at 0, 200, 400, & 600 kg ha ⁻¹	Sigmoidal response: Tuber yield increased up to 200 kg of compound NPK/ha and was similar up to 600 kg ha ⁻¹	Sigmoidal response: Tuber weight increased up to 400 kg compound NPK/ha and was similar at 600 kg ha ⁻¹ Quadratic response: Tuber number increased up to 400	Katuromunda <i>et al.</i> 2021

			kg compound NPK/ha and decreased at 600 kg ha ⁻¹	
			Sigmoidal response: Tuber length increased up to 200 kg of compound NPK/ha and was similar up to 600 kg ha ⁻¹	
			Sigmoidal response: Tuber diameter increased up to 400 kg compound NPK/ha and was similar at 600 kg ha ⁻¹	
Cassava	Urea (46% N) at 0, 100 kg ha ⁻¹ TSP (46% P ₂ O ₅) at 0, 22 kg ha ⁻¹ MOP (50% K ₂ O) at 0, 83 kg ha ⁻¹ (NPK)	Positive response: Tuber yield increased with application of NPK as urea, TSP, and MOP	No response: Tuber weight did not respond to fertiliser application Positive response: Tuber number increased with application of NPK as urea, TSP, and MOP	Munyahali <i>et al.</i> 2017
Cassava	Urea (46% N) at 0, 217 kg ha ⁻¹ TSP (46% P ₂ O ₅) at 0, 150 kg ha ⁻¹	Positive response: Tuber yield increased with application of NPK as urea, TSP, and MOP	Positive response: Tuber weight increased with application of NPK as urea, TSP, and MOP	Mwamba <i>et al.</i> 2021

	MOP (50% K ₂ O) at 0, 160 kg ha ⁻¹ (NPK)		Positive response: Tuber number increased with application of NPK as urea, TSP, and MOP	
			Positive response: Tuber diameter increased with application of NPK as urea, TSP, and MOP	
Aquatic taro	Urea (46.4% N) at 0, 75, 100, & 125 kg ha ⁻¹ TSP (46% P ₂ O ₅) at 0, 30, 45, & 60 kg ha ⁻¹ MOP (60% K ₂ O) at 0, 80, 100, & 120 kg ha ⁻¹ (NPK)	Quadratic response: Tuber yield increased up to 100 kg of urea/ha + 45 kg TSP/ha + 100 kg MOP/ha and decreased with combination of higher levels of urea, TSP, and MOP	Sigmoidal response: Tuber number increased up to 100 kg of urea/ha + 60 kg TSP/ha + 120 kg MOP/ha and was similar with application of 125 kg urea/ha + 60 kg TSP/ha + 120 kg MOP/ha Sigmoidal response: Tuber length increased up to 100 kg urea/ha + 45 kg TSP/ha + 100 kg MOP/ha and was similar with application of 125 kg urea/ha + 60 kg TSP/ha + 120 kg MOP/ha	Noor <i>et al.</i> 2015
Beetroot	Urea (46% N) at 0, 46, 92, & 138 kg ha ⁻¹	Quadratic response: Tuber yield increased up to 92 kg of urea/ha and decreased with application of 138 kg ha ⁻¹	Sigmoidal response: Tuber weight increased up to 92 kg urea/ha and was similar at 138 kg ha ⁻¹ Sigmoidal response: Tuber length increased up to 92 kg	Sinta and Garo, 2021

			urea/ha and was similar at 138 kg ha ⁻¹	
			Sigmoidal response: Tuber diameter increased up to 92 kg urea/ha and was similar at 138 kg ha ⁻¹	
Taro	MOP (60% K ₂ O) at 136, 203, & 271 kg ha ⁻¹	Not recorded	Quadratic response: Tuber weight increased up to 203 kg of MOP/ha and decreased with the application of 271 kg ha ⁻¹	Suminarti <i>et al.</i> , 2022
Jerusalem artichoke	Urea (46% N) at 0, 80, & 120 kg ha ⁻¹	Positive response: Tuber yield increased up to 120 kg urea/ha	Not recorded	Wierzbowska <i>et al.</i> 2021
Potato	Not recorded (0, 60, 120, & 180 kg N/ha)	Positive response: Tuber yield increased up to 180 kg N/ha	Sigmoidal response: Tuber number increased up to 60 kg N/ha and was similar up to 180 kg ha ⁻¹	Kołodziejczyk, 2014
			Positive response: Tuber weight increased up to 180 kg N/ha	
Potato	AN (34% N) at 0, 50, 100, 150, 200, & 250 kg ha ⁻¹	Sigmoidal response: Tuber yield increased up to 150 kg AN/ha and was similar up to 250 kg ha ⁻¹	Sigmoidal response: Tuber weight increased up to 150 kg AN/ha and was similar up to 250 kg ha ⁻¹	Zebarth <i>et al.</i> 2011

Potato	Urea (46.4% N) at 0, 75, 150, 225, & 300 kg ha ⁻¹	Quadratic response: Tuber yield increased up to 225 kg urea/ha and decreased at 300 kg ha ⁻¹	Quadratic response: Tuber number increased up to 225 kg urea/ha and decreased at 300 kg ha ⁻¹	Mozumder <i>et al.</i> 2014
Potato	Urea (46% N) at 0, 40, & 120 kg ha ⁻¹	Positive response: Tuber yield increased up to 120 kg urea/ha	Positive response: Tuber weight increased up to 120 kg urea/ha	Getahun <i>et al.</i> 2019
Potato	AN (34% N) at 0, 30, 60, & 90 kg ha ⁻¹	Sigmoidal response: Tuber yield increased up to 30 kg AN/ha and was similar up to 90 kg ha ⁻¹	Positive response: Tuber number increased up to 120 kg urea/ha Not recorded	Nurmanov <i>et al.</i> 2019
Potato	Urea (46.4% N) at 0, 75, 150, 225, & 300 kg ha ⁻¹	Quadratic response: Tuber yield increased up to 225 kg urea/ha and decreased at 300 kg ha ⁻¹	Sigmoidal response: Tuber number increased up to 225 kg urea/ha and was similar at 300 kg ha ⁻¹	Yadav <i>et al.</i> 2022
Potato	MOP (60% K ₂ O) at 0, 30, 60, 90, 120, 150, 180, 210, 240, 270, & 300 kg ha ⁻¹	Quadratic response: Tuber yield increased up to 150 kg MOP/ha and slightly decreased up to 300 kg ha ⁻¹	Not recorded	Haile and Boke, 2011

Potato	SOP (50% K ₂ O) at 0, 150, & 225 kg ha ⁻¹ , MOP (60% K ₂ O) at 0, 150, & 225 kg ha ⁻¹	Sigmoidal response: Tuber yield increased up to 150 kg SOP/ha and 150 kg MOP/ha and was similar at 225 kg SOP/ha and 225 kg MOP/ha	Not recorded	Khan <i>et al.</i> 2010
Potato	0, MOP (60% K ₂ O) at 166 kg ha ⁻¹ , SOP (50% K ₂ O) at 166 kg ha ⁻¹ & Patentkali (30% K ₂ O) at 166 kg ha ⁻¹	Positive response: Tuber yield increased with the application of K ₂ O; MOP ranking the highest	Not recorded	Grzebisz <i>et al.</i> 2020
Potato	MOP (60% K ₂ O) at 0, 100, & 150 kg ha ⁻¹	Sigmoidal response: Tuber yield increased up to 100 kg MOP/ha and was similar at 150 kg ha ⁻¹	Not recorded	Yakimenko and Naumova, <i>et al.</i> 2021
Potato	Not recorded (0, 50, 100, & 150 kg P/ha)	Not recorded	Sigmoidal response: Tuber weight increased up to 50 kg P/ha and was similar up to 150 kg ha ⁻¹ Sigmoidal response: Tuber number increased up to 50 kg	Manorama <i>et al.</i> 2017

			P/ha and was similar up to 150 kg ha ⁻¹	
Potato	Urea (46% N) at 0, 50, 100, 150, & 200 kg ha ⁻¹ TSP (46% P ₂ O ₅) at 0, 50, 100, 150, & 200 kg ha ⁻¹	No response: Tuber yield did not increase with application of NP as urea and TSP	No response: Tuber weight and number did not increase with application of NP as urea and TSP	Setu and Mitiku, 2019
Potato	AS (34% N) at 0, 120, & 160 kg ha ⁻¹ MOP (60% K ₂ O) at 0, 80, 160, & 240 kg ha ⁻¹	Positive response: Tuber yield increased with the application of 120 kg AS/ha and 160 kg MOP/ha	Not recorded	Grzebisz <i>et al.</i> 2018
Potato	TSP (46% P ₂ O ₅) at 0, 34.5, & 69 kg ha ⁻¹ MOP (60% K ₂ O) at 0, 100, 200, & 300 kg ha ⁻¹	Quadratic response: Tuber yield increased up to 34.5 kg TSP/ha + 200 kg MOP/ha and decreased with a combination of higher levels of TSP, and MOP.	Not recorded	Gelaye <i>et al.</i> 2022
Potato	Not recorded	Positive response: Tuber yield increased with the application of NP and balanced NPK	Positive response: Tuber number increased with the application of NP	Tan <i>et al.</i> 2016

	(0, 150, 210, & 225 kg N/ha)			
	(0, 60 & 90, & 120 kg P/ha)			
	(0, 60, & 90 kg K/ha)			
Potato	Compound NPK (4N ⁻¹ 8P ₂ O ₅ - 4K ₂ O) at 0, 1.5, 3.0, & 4.5 t/ha	Quadratic response: Tuber yield increased up to 1.4 t/ha of compound NPK and decreased at 2.1 t/ha	Not recorded	Yagi <i>et al.</i> 2019
	(6N- 30P ₂ O ₅ - 6K ₂ O) at 0, 0.7, 1.4, & 2.1 t/ha			
Potato	Compound NPK (0, 113, 150, 188, & 225 kg N/ha)	Positive response: Tuber yield increased up to the highest levels of compound NPK	Not recorded	Sandhu <i>et al.</i> 2013
	(0, 38, 50, 63, & 75 kg P/ha)			

	(0, 75, 100, 125, & 150 kg/ K ha)			
Potato	Compound NPK (4N ⁻¹ 4P ₂ O ₅ - 8K ₂ O) at 0, 2, 4, & 6 t/ha	Quadratic response: Tuber yield increased up to 4 t/ha of compound NPK and decreased at 6 t/ha	Sigmoidal response: Tuber weight increased up to 4 t/ha of compound NPK and was similar at 6 t/ha Sigmoidal response: Tuber number increased up to 4 t/ha of compound NPK and was similar at 6 t/ha	Santos <i>et al.</i> 2018

2.3.4 Impact of application rates of nitrogen-based fertilisers on yield and yield components of root and tuber crops

Of the included 34 publications, 11 evaluated the effect of N application rate on the growth and yield of RTCs. Only two of the 11 publications evaluated the effect of N application rates on sweet potato (Duan *et al.*, 2018; Duan *et al.*, 2019). In a two-year research to evaluate the effect of N on different sweet potato cultivars, Duan *et al.* (2018) observed that the application of N reduced the tuberous root yield, weight and number. For all the varieties that were evaluated, the maximum value of all the measured parameters was attained in the control plots with no N fertiliser applied (Duan *et al.*, 2018). Tuber number decreased by 7.1% and 29.5% after the application of 75 kg urea ha⁻¹ and 150 kg urea ha⁻¹, respectively. However, Duan *et al.* (2019) by evaluating the response of a new Chinese sweet potato to different N rates, discovered a quadratic response in tuber yield and a sigmoidal response in tuber weight. For tuber yield, the application of 75 kg urea ha⁻¹ resulted in the highest tuber yield of 41.3 t ha⁻¹, and an increase in N applied to 150 kg urea ha⁻¹ resulted in a lower yield of 36.3 t ha⁻¹. Tuber weight increased by 30.99% with the application of 75 kg urea ha⁻¹ and the response was not significantly different with an application of 150 kg urea ha⁻¹ (Duan *et al.*, 2019).

Of the 11 included studies that evaluated the effect of N application rate on the growth and yield of RTCs, only one study evaluated the response of cassava growth and yield to the application of N fertiliser (Mota et al., 2020). In this study, Mota *et al.* (2020) found that different N application rates supplied during the second vegetative cycle had no significant effect on cassava tuber length and diameter. However, tuber yield showed a sigmoidal response and tuber number showed an asymptotic response. Tuber yield increased by 5% with the application of 50 kg urea ha⁻¹ and there was no significant increase in tuber yield with an increase in application rates (Mota *et al.*, 2020). Furthermore, Mota *et al.* (2020) observed an increasing trend in tuber number per plant with an increase in urea application rate. Tuber number per plant increased by 2.3%, 4.5%, 6.8% and 9% with application of 50 kg, 100 kg, 150 kg, and 200 kg urea ha⁻¹, respectively.

In a study to evaluate the influence of plant spacing and N fertiliser rates on yield components of beetroot, an increase in the application rate up to 92 kg urea ha⁻¹ caused an increase in root yield (Sinta & Garo, 2021). Moreover, a decrease in the trend was observed with a further increase in the application rate up to 138 kg urea ha⁻¹. However, beetroot weight, length, and diameter did not decrease with higher urea application rates. The root weight and diameter increased by 14% and 24% with the application of 92 kg urea ha⁻¹ and there was no significant increase in root weight or diameter with the application of 138 kg urea ha⁻¹. Another study that evaluated the influence of N fertiliser on tuber yield and yield components was by Wierzbowska et al. (2021). Wierzbowska *et al.* (2021) by evaluating the effect of N fertiliser application rates on different cultivars of Jerusalem artichoke, observed that tuber yield increased with an increase in N rate. The highest tuber yield of 33.32, 38.23, and 40.99 t ha⁻¹ (2016, 2017, 2018, respectively) was observed in the *Gute Gelbe* cultivar at the highest application rate of 120 kg urea ha⁻¹.

Six of the 11 studies that evaluated the effect of N application rate on the growth and yield of RTCs, evaluated the response of potato growth and yield to the application of N fertiliser (Getahun et al., 2020; Kołodziejczyk, 2014; Mozumder et al., 2014; Nurmanov et al., 2019; Yadav et al., 2022; Zebarth et al., 2011). Two of the studies observed a quadratic response to increasing rates of urea fertiliser (Mozumder *et al.*, 2014; Yadav *et al.*, 2022). In an evaluation of potato cultivars for productivity and N requirement, a sharp increase in tuber yield was observed up to 225 kg urea ha⁻¹ and a slight decrease in tuber yield with the application of 300 kg urea ha⁻¹ (Mozumder *et al.*, 2014; Yadav *et al.*, 2022). The same trend was also true in tuber

number per plant, the tuber number per plant was highest (3.88) at an application rate of 225 kg urea ha⁻¹ and reduced to 3.76 at an application rate of 300 kg urea ha⁻¹ (Mozumder *et al.*, 2014). Furthermore, a number of the measured parameters showed a sigmoidal response to an increase in N application rates. Tuber weight and yield initially increased linearly with the application of N fertiliser and a yield ceiling was observed at an optimum N application rate of 150 kg AN ha⁻¹ (Zebarth *et al.*, 2011) and 30 kg AN ha⁻¹ (Nurmanov *et al.*, 2019). The same trend was also observed in tuber number, reaching its ceiling at an application rate of 60 kg N ha⁻¹ (Kołodziejczyk, 2014), and 225 kg urea ha⁻¹ (Yadav *et al.*, 2022). There was no significant change in potato yield observed with a further increase in N fertiliser application rate.

Two of the 11 studies discovered a significant asymptotic response in potato tuber yield and yield parameters with an increase in the amount of N fertiliser (Getahun *et al.*, 2020; Kołodziejczyk, 2014). Each applied N dose caused a marked increase in potato yield as compared with a smaller dose. The increment in potato yield ranged from 72.5% with the application of 60 kg urea ha⁻¹ to 140% with the application of 180 kg urea ha⁻¹ (Kołodziejczyk, 2014). Furthermore, Getahun *et al.* (2020) observed that N application rates linearly increased tuber yield, weight and number.

2.3.5 Impact of application rate of phosphorus-based fertilisers on yield and yield components of root and tuber crops

Only three studies out of the included 34 evaluated the effect of P application rates on yield and yield components of RTCs (Luz *et al.*, 2013; Manorama *et al.*, 2017; Munda *et al.*, 2019). In a study to evaluate the response of sweet potato to moderate P application under an intercropping system, Munda *et al.* (2019) observed that the mean tuber yield increased by 25.4% up to 20 kg SSP ha⁻¹ and the mean yield was not significantly different at 40 kg SSP ha⁻¹. Similarly, research on the influence of P on sweet potato yield, showed an increase in total tuber productivity until a yield ceiling was reached at an application rate of 600 kg SSP ha⁻¹ (Luz *et al.*, 2013). One of these studies reported the effects of P application rates on potato tuber yield and yield parameters (Manorama *et al.*, 2017). In an evaluation of P efficiency in potato cultivars, increasing P₂O₅ fertiliser from 0 to 50 kg ha⁻¹ caused an increase in tuber number per plant and tuber weight by 22% and 27.9%, respectively in P efficient varieties (Manorama *et al.*, 2017). A further increase in the P₂O₅ fertiliser application rate had no significant effect on these potato yield components.

2.3.6 Impact of rate of potassium-based fertilisers on yield and yield components of root and tuber crops

Eight of the 34 publications (n = 69) evaluated the effects of K fertiliser application rates. Of the eight studies, two publications evaluated the effect of K₂O application rates on sweet potato (Aboyaji *et al.*, 2019; Wang *et al.*, 2014). Sweet potato yield and yield parameters responded differently to the application of K fertilisers. In a study to evaluate the response of sweet potato quality to different levels of K fertiliser on a tropical alfisol, Aboyaji *et al.* (2019) observed that tuber yield increased by 133% at an application rate of 80 kg MOP ha⁻¹ and further increases in MOP fertiliser decreased tuber yield. However, in an evaluation of the variation in K uptake and utilisation among sweet potato varieties, Wang *et al.* (2014) observed an increase in tuber yield and weight up to a yield ceiling of 300 kg SOP ha⁻¹ and 150 kg SOP ha⁻¹ respectively. Furthermore, the application of K fertiliser led to a linear increase in tuber number per plant up to 25.7% at the highest application rate that was evaluated (450 kg SOP ha⁻¹).

Only one of the eight studies that evaluated the effects of K fertiliser application rates focused on cassava (Gonçalves *et al.*, 2022). In a study to evaluate the effect of K sources on cassava plant productivity, Gonçalves *et al.* (2022) realised that high quantities of K reduced tuber yield, number and diameter. Tuber yield, number per plant and diameter reached a maximum yield at 60 kg SOP ha⁻¹ and a slight decrease was observed with the application of 90 kg SOP ha⁻¹ and 120 kg SOP ha⁻¹ (Gonçalves *et al.*, 2022). Tuber yield, number per plant and diameter increased by 49%, 15.1% and 7.5%, respectively. Another study of the eight evaluated the influence of K application on the improvement of taro mbothe yield (Suminarti *et al.*, 2022). Application of MOP up to a rate of 203 kg ha⁻¹ caused an increase in mean tuber weight by 5.7% and further increase in MOP to 271 kg of MOP ha⁻¹ reduced mean tuber weight (Suminarti *et al.*, 2022).

Four of the eight studies that evaluated the effect of K application rate on the growth and yield of RTCs, evaluated the response of potato growth and yield. In a study evaluating potato response to potassium application in acidic soils, tuber yield increased sharply by 105.3% with K application rates up to 150 kg MOP/ha, but a slight decrease in yield was observed when the rate was increased to 300 kg MOP/ha (Haile, 2011). However, in two of the studies tuber yield increased with an increase in K fertiliser rates until yield ceilings at 100 kg MOP/ha (Yakimenko & Naumova, 2021), 150 kg MOP ha⁻¹ and 150 kg SOP ha⁻¹ (Khan *et al.*, 2010). Furthermore, in another study on the effect of K on potato yield, the application of K fertiliser

(166 kg MOP ha⁻¹) increased the tuber yield by 60% compared to the control (Grzebisz et al., 2020).

2.3.7 *Impact of combinations of two macronutrients on yield and yield components of root and tuber crops*

Of the studies (n = 84) that evaluated the effect of the application of different combinations of macronutrients on the root and tuber yield of RTCs, one focused on the effect of combining N and K fertiliser (NK) on cassava (Uwah et al., 2013). In a study to evaluate the response of newly released cassava varieties to NK fertilisers, Uwah *et al.* (2013) found that the combination of NK and their application rates had no significant effect on cassava tuber yield and tuber length. However, Grzebisz et al. (2018) by evaluating the combination of different rates of NK, noted a significant increase in potato tuber yield. The highest yield was obtained with the application of 120 kg AS ha⁻¹ and 160 kg MOP ha⁻¹, which was not significantly different from that obtained after the application of 160 kg AN ha⁻¹ and 160 kg MOP ha⁻¹.

Another combination of macronutrients which was evaluated was of N and P fertiliser (NP). In evaluating the response of potato to NP fertilisers at Assosa, western Ethiopia, Setu and Mitiku (2020) found that the combination of NP and their application rates had no significant effect on potato tuber yield and tuber length. Another study evaluated the growth and quality of potato as influenced by a combination of P and K (PK) (Grzebisz *et al.*, 2018). The results showed an increase in potato stolon yield in response to applied PK up to 34.5 kg TSP/ha + 200 kg MOP/ha and a further increase in the application rate of both P and K resulted in a decrease in stolon yield. Furthermore, another study evaluated balanced fertiliser management strategy that can enhance potato yield and marketing quality by evaluating the effect of omitting N, P, and K from a balanced NPK fertiliser package (Tan *et al.*, 2016). Tan *et al.* (2016) found that tuber yield and tuber number per plant were increased with application of NP and balanced NPK. The results showed that N, P, and K contributed 18%, 14%, and 13%, respectively, to the tuber yield increase in potato across the three years of study.

2.3.8 *Impact of application rates of compound NPK fertilisers on yield and yield components of root and tuber crops*

Of the included studies, seven evaluated the effect of NPK as compound NPK fertiliser and as combined N, P, and K doses of straight fertilisers. Three of the seven studies evaluated the

effect of application rates of compound NPK fertilisers on cassava tuber yield (Katuromunda et al., 2021; Munyahali et al., 2017; Mwamba et al., 2021). In an evaluation of cassava growth and yield responses to NPK fertiliser, Munyahali *et al.* (2017) found that different NPK application rates had no significant effect on cassava tuber weight. However, mean tuber number and storage root yield showed a positive response to the application of NPK. Cassava storage root yield and tuber number increased by 19.9% and 20% with the application of NPK (Munyahali *et al.*, 2017). Another positive response to NPK application was observed in tuber number per plant, diameter, weight, and yield (Mwamba *et al.*, 2021). Application of compound NPK fertiliser increased cassava weight, and root tuber yield compared to control plots (no fertiliser) by 51% and 27% respectively (Mwamba *et al.*, 2021). Furthermore, in evaluating the performance of newly developed cassava varieties in response to NPK fertiliser Katuromunda *et al.* (2021) discovered a sigmoidal response in tuber yield, weight, length and diameter. An increase in application rate of NPK increased tuber yield and length up to an application rate of 200 kg NPK ha⁻¹. Increasing compound NPK fertiliser rates up to 200 kg ha⁻¹ increased tuber yield by 68.3% and 67.6% in NAROCASS 1 and NASE 14 cassava varieties, respectively (Katuromunda *et al.*, 2021). Moreover, mean tuber weight and diameter increased by 46.3% and 133.4% (respectively) to a yield ceiling at 400 kg NPK ha⁻¹. However, a quadratic response was observed in the tuber number per plant. An increase in tuber number per plant was observed up to 400 kg NPK ha⁻¹ and a further increase in NPK slightly reduced the number of tubers per plant (Katuromunda *et al.*, 2021).

The effect of NPK fertiliser was also evaluated on aquatic taro stolon yield, number and length (Noor *et al.*, 2015). In a study to find the optimum doses of NPK on aquatic taro, stolon yield showed a quadratic response to an increase in NPK application rates (Noor *et al.*, 2015). The highest stolon yield of 28.16 t ha⁻¹ was recorded at an NPK application rate of 100 kg N ha⁻¹, 45 kg P ha⁻¹, and 100 kg K ha⁻¹. Stolon number per plant and stolon length showed a sigmoidal response to an increase in NPK application rate. Stolon number initially increased linearly with the application of NPK fertiliser until a yield ceiling was observed at an optimum NPK application rate of 100 kg of urea/ha + 60 kg TSP ha⁻¹ + 120 kg MOP ha⁻¹ and the stolon number was similar with an increase N dose in NPK to 125 kg urea/ha + 60 kg TSP ha⁻¹ + 120 kg MOP ha⁻¹ (Noor *et al.*, 2015). Similarly, stolon length increased with an increase in NPK up to a yield ceiling at 100 kg urea/ha + 45 kg TSP ha⁻¹ + 100 kg MOP ha⁻¹ and the stolon length was not significantly different with an increase in NPK to 125 kg urea/ha + 60 kg TSP ha⁻¹ + 120 kg MOP ha⁻¹ (Noor *et al.*, 2015).

Four of the seven studies that evaluated the effect of NPK fertiliser, focused on the response of potato. In a research to evaluate potato yield response to NPK fertiliser formulas, tuber yield showed a quadratic response to an increase in NPK fertiliser (Santos et al., 2018; Yagi et al., 2019). A significant increase in tuber yield by 32.04% was observed with an increase in compound NPK (4% N: 14% P: 8% K) up to 4 t ha⁻¹, and a further increase in compound NPK fertiliser to 6 t ha⁻¹ slightly reduced tuber yield (Santos *et al.*, 2018). Similarly, Yagi *et al.* (2019) observed the highest tuber yield of 34.9 t ha⁻¹ at an application rate of 1.4 t ha⁻¹ compound NPK (4% N: 18% P: 4% K) fertiliser, and a further increase in the NPK application rate to 2.1 t ha⁻¹ resulted in a decrease in tuber yield. However, in evaluating the effect of application rates of NPK as combined N, P, and K doses of straight fertilisers, potato tuber yield showed a positive response to NPK fertiliser rates (Sandhu et al., 2013). Tuber yield increased with every increase in NPK dose to the highest level of NPK assessed. The highest tuber yield of 308 t ha⁻¹ was attained at 225 kg of N ha⁻¹ + 75 kg P ha⁻¹ + 150 kg K ha⁻¹ (Sandhu *et al.*, 2013). A different respond was observed in a study by Santos *et al.* (2018) who evaluated the responses of new potato genotypes to different rates of NPK fertiliser. They found that tuber weight and the number of tubers per plant showed a sigmoidal response to application rates of NPK. Mean tuber weight and number increased by 21% and 45%, respectively, with compound NPK application rates up to 4 t ha⁻¹ and there was no significant increase with application of 6 t/ha compound NPK (Santos *et al.*, 2018).

2.3.9 Risk of bias assessment

The ‘risk of bias’ assessment is indicated in Figure 2.8. Eight studies (22%) were judged to have a low risk of bias, sixteen studies (44%) to have some concerns, and twelve studies (33%) to have high risk of bias. Individual risk of bias judgements for the included studies are presented in supplementary material 1.

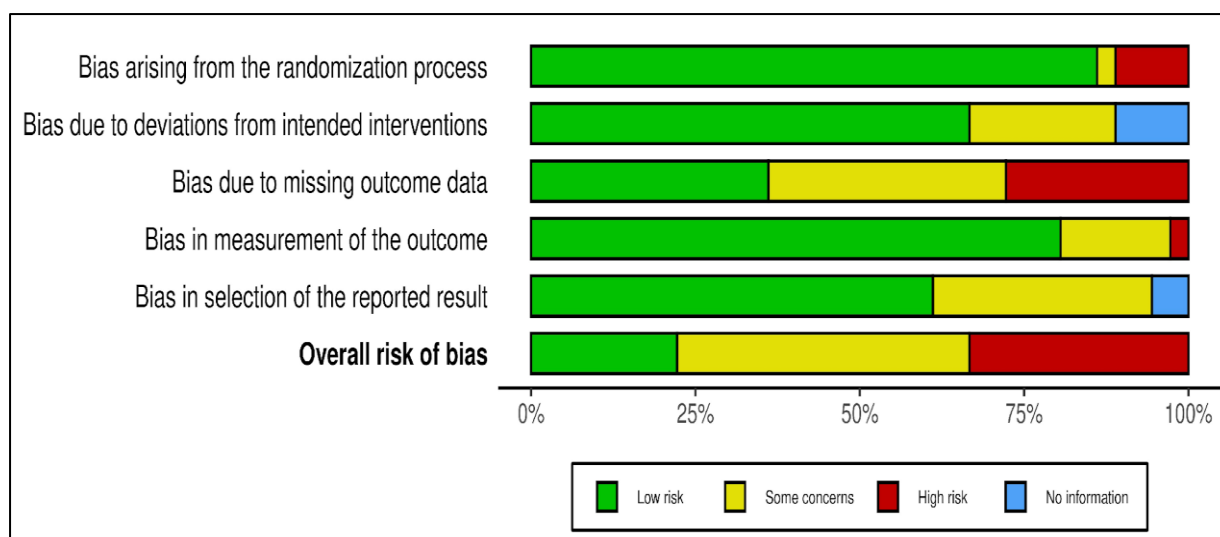


Figure 2.7: Risk of bias summary plot.

2.4 Discussion

2.4.1 The frequently assessed RTCs plant type, growth parameter and tuber quality

In this systematic review, the most commonly studied RTCs were potato, cassava, and sweet potato. Potato dominated most production areas due to its high nutritional value (Nanbol and Namo (2019) and wide adoption as a major food crop in highland regions of many continents (Chandrasekara & Josheph Kumar, 2016). In tropical and sub-tropical regions, people widely consume potato for its dietary energy, and they have adopted it as a staple food (Tan *et al.*, 2016). This is likely because of its ability to produce more edible-energy in a shorter period than other RTC species (Torabian *et al.*, 2021). In addition, potato is also an excellent source of vitamins, K, magnesium, dietary fibre, iron, and phenolic acids that are deficient in other major RTCs (Jansky *et al.*, 2019). Cassava was the second most studied crop, which might be because it is the most widely cultivated root crop in the tropical regions of the world (Katuromunda *et al.*, 2021). Furthermore, the frequent evaluation of cassava production in Africa might be attributed to its high calorific value, famine-security, and drought tolerance characteristics (Alexandratos & Bruinsma, 2012; Daryanto *et al.*, 2017).

In terms of RTC's growth parameters, the results showed that plant height was one of the most assessed parameters most probably because it is an important morphological and developmental attribute indicating overall plant health, growth and development (Mwamba *et al.*, 2021; Wang *et al.*, 2018). In fact, the assessed studies reported a direct correlation between plant height and shoot biomass, and yield parameters (Getahun *et al.*, 2020; Hu *et al.*, 2018;

Munyahali *et al.*, 2017; Mwamba *et al.*, 2021). Therefore, to assess plant growth rate, regular measurement of plant height at different growth stages becomes crucial. In addition, plant height is a significant growth parameter because of its potential impact on the plants' ability to compete for light or capture light (Moles *et al.*, 2009; Munda *et al.*, 2019). Furthermore, plant height is also regarded as an indicator of plant health and plants' potential to outcompete weeds, thus explaining its frequent occurrence in the evaluated studies (Freeman *et al.*, 2007; Hu *et al.*, 2018). In contrast, Freeman *et al.* (2007), based on their findings, argued that plant height may not directly correlate to tuber growth and yield at all growth stages but at late growth stages.

In terms of root and tuber quality, proximate analysis was the commonly assessed parameter in the included studies. This stems from the importance of chemical and nutritional composition in entailing the nutritional value and suitability of RTCs for human and livestock consumption and industrial use (Gonçalves *et al.*, 2022; Grzebisz *et al.*, 2020; Wierzbowska *et al.*, 2021). In addition, the emphasis on proximate analysis could be attributed to the significant impact of fertiliser application on the nutritional composition of plants (Khan *et al.*, 2012; Khan *et al.*, 2010; Wang *et al.*, 2008). Notably, the assessed studies have shown that K and nitrogen-based fertilisers significantly influence the composition of vitamin C in potato (Khan *et al.*, 2012; Khan *et al.*, 2010). They also influence phenolic compounds and glycoalkaloids in cassava (Chandrasekara and Josheph Kumar (2016) as well as starch content and quality in RTCs (Aboyeji *et al.*, 2019; Duan *et al.*, 2019; Katurumunda *et al.*, 2021; Uwah *et al.*, 2013; Wang *et al.*, 2018). Similarly, Eppendorfer and Eggum (1994) supported carrying out proximate analysis of roots and tubers following fertiliser application, after discovering that starch content in tubers responded to fertiliser application in a pattern similar to tuber yield.

2.4.2 Impact of nitrogen-based fertiliser on yield and yield components of root and tuber crops

One of the most important factors affecting the growth and yield of RTCs is nutrient availability. In recent years, significant advancements in scientific research have led to the development of improved nutrient management practices for the production of root and tuber crops. This systematic literature review has focused on providing a comprehensive synthesis of the existing research on the effects of N, P, and K fertilisers on the tuber yield of RTCs.

The systematic literature review showed that of the three assessed macronutrients, N was the most studied, with a greater effect on RTC yield parameters (Noor *et al.*, 2015; Uwah *et al.*, 2013). This is because N is an essential macronutrient in plant growth and is required for the morphological and physiological processes of plants, which are key determinants of tuber yield (Uwah *et al.*, 2013). In plant growth, N enhances cell division of meristematic cells and stimulates growth of meristematic tissues, enhancing leaf area expansion that results in increased LAI and radiation interception (Rademacher & Nelson, 2001). In addition, N is a key component of plant dry matter, making up to 4% of it (Kahsay, 2019).

The reviewed reports about N fertilisers' impact on the yield of RTCs varied within and across plant species. Some studies indicated no response to an increase in N fertiliser, while others showed a low or high crop response. This might be attributed to the differences in nutrient uptake efficiency, nutrient use efficiency, nutrient demand, nutrient storage capacity, and nutrient resorption efficiency of the plant species (Melteras *et al.*, 2008; Zhu *et al.*, 2023). The significant positive response of potato yield with an increase in N reported by Mozumder *et al.* (2014) and Kołodziejczyk (2014) might be attributed to an increase in tuber numbers per stem and tuber fresh weight. Kołodziejczyk (2014) noted that at an application rate of 180 kg N ha⁻¹, tuber numbers per stem led to a 5.7% increment in tuber yield and tuber fresh weight led to a 96.6% increase in tuber yield. This might be owing to the availability of N, a key nutrient that enhances leaf area expansion, hence increasing LAI and light interception (Tajul *et al.*, 2013). Increased LAI during tuber initiation and tuber bulking periods results in increased dry matter accumulation, the number of tubers per stem, and tuber weight (Mozumder *et al.*, 2014). This was true in research by Premi *et al.* (2012), who discovered a positive correlation between tuber yield, plant height, and tuber bulking ratio with an increase in N fertiliser. Similarly, Uwah *et al.* (2013) credited tuber yield's positive response to an increase in N at the early onset of the tuber initiation stage and an increase in tuber bulking rate.

N also plays a crucial role in enhancing growth because it is a constituent of chlorophyll and protein. Therefore, an increase in N fertiliser rates results in an increase in radiation interception and photosynthetic rates, thereby enhancing the production of more photo-assimilates that are partitioned to tuber growth (Mozumder *et al.*, 2014; Noor *et al.*, 2015). Changes in application rates of N do not always cause an increase in tuber weight, length, diameter, or yield (Mota *et al.*, 2020). This might be attributed to the time of application of the N fertilisers. Application of N in the second vegetative cycle of perennial RTCs might cause

greater vegetative growth only at the expense of tubers. Zhou *et al.* (2017) also observed a decrease in N efficiency at high air temperatures, which was also true in yams. Likewise, Mozumder *et al.* (2014) discovered a decline in tuber yield with the application of N beyond 225 kg ha⁻¹, and the authors credited it to following the principle of the law of diminishing returns.

In most of the studies that assessed N application rates, there was a decrease in tuber yield and root dimensions with an increase in N fertiliser beyond an optimum rate. This showed diminishing returns in yield with increased application of N beyond the optimum N rate (Mozumder *et al.*, 2014). Moreover, increasing rates of N may cause imbalanced nutrient availability that might lead to lower uptake of other essential nutrients, thus decreasing dry matter accumulation and tuber yield (Tan *et al.*, 2016). Duan *et al.* (2019) noted that increasing N rates might decrease top-to-base amino acid and K⁺ gradients. This leads to an undesirable top-to-base sucrose gradient along the stem (Duan *et al.*, 2019). This will result in excess vegetative growth at the expense of the sweet potato tubers. Similarly, Yadav *et al.* (2022) indicated that the decrease in potato tuber yield at higher rates of N might be due to the partitioning of assimilates into shoots rather than tubers. Excessive vegetative growth might also result in mutual shading of plant leaves, thus decreasing surface area for radiation interception, causing a decrease in canopy photosynthesis, net assimilation rate and transport of assimilates to roots and tubers (Mwamba *et al.*, 2021). According to Wierzbowska *et al.* (2021), the sigmoidal response of Jerusalem artichoke to the high application of N might be because of the low N use efficiency. Similarly, in potato, Grzebisz *et al.* (2017) explained the sigmoidal response to be attributed to a decrease in agronomic efficiency of N with an increase in N fertiliser rates thus reducing tuber yield.

2.4.3 Impact of phosphorus-based fertiliser on yield and yield components of root and tuber crops

Root and tuber crops also require P, a macronutrient essential for all energy reactions that require but not limited to AMP, ADP, and ATP (Scheerer *et al.*, 2019). In this systematic review, the positive response of tuber yield to increasing rates of P showed the essential role of P in plant development (Luz *et al.*, 2013; Manorama *et al.*, 2017; Munda *et al.*, 2019). The asymptotic response in potato to increase in P rates observed by Luz *et al.* (2013) up to the highest dose assessed, showed the importance of P in tuber initiation and tuber productivity. As a result, this increased the number of tubers per plant and tuber yield (Luz *et al.*, 2013). The

results showed that P is also a key nutrient for stimulating tuberisation and accelerating maturation, thus explaining the positive tuber yield response (Luz *et al.*, 2013). Munda *et al.* (2019) indicated that applying P fertiliser in sweet potato significantly increased vegetative growth parameters. Particularly, P proved to increase the number of sweet potato leaves per vine, increasing the surface area for photosynthesis and producing more assimilates (Hassan *et al.*, 2005; Munda *et al.*, 2019). However, the evaluated studies showed that there is no positive correlation between high rates of P and tuber size or tuber weight in sweet potato (Manorama *et al.*, 2017; Munda *et al.*, 2019). This may be brought on by the roots' inability to efficiently absorb P. Manorama *et al.* (2017) indicated that poor morphological root characteristics and changes in soil pH might impair the roots' ability to absorb P. In addition, according to Gelaye *et al.* (2022), the decrease in root and tuber yield at higher application rates can be attributed to nutritional imbalances, which in turn lead to yield depression and reduced tuber production.

2.4.4 Impact of potassium-based fertiliser on yield and yield components of root and tuber crops

A total of eight studies in this systematic review evaluated the effect of K application rate on RTC growth and yield. This might be because of its crucial contribution to RTCs' productivity. Potassium is one of the major plant nutrients and an essential osmoticum that maintains cells through turgor pressure (Torabian *et al.*, 2021). It also plays a crucial role in the completion of physiological and metabolic processes in plants such as root elongation, leaf expansion, and the transport of assimilates from source to sink organs (Oddo *et al.*, 2011).

The positive and sigmoidal response in potato to an increase in K doses might be due to its importance in the metabolic processes (Grzebisz *et al.*, 2020; Khan *et al.*, 2012; Khan *et al.*, 2010). These include but are not limited to protein and starch synthesis, stoma opening and closing, water and sugar transport, and photosynthetic processes (Prajapati & Modi, 2012). However, a slight decrease in potato tuber yield due to an increase in K application rate after reaching a peak yield might be due to an imbalance in plant nutrition that favours excessive K over other essential nutrients (Haile, 2011). Therefore, it is not recommended to apply high rates of K as it affects uptake of other nutrients mainly calcium and magnesium thus reducing tuber yield (Grzebisz *et al.*, 2020; Yakimenko & Naumova, 2021).

The increase in tuberous root weight and yield observed in sweet potato, taro and cassava was also attributed to the key role of K in cell division, and activation of several enzymatic reactions

that enhances tuber growth and yield (Aboyaji et al., 2019; Suminarti et al., 2022; Wang et al., 2014). Furthermore, K is also important in regulating transport of water in plants thus contributing to increased translocation of starch and other photoassimilates that used in rapid tuber development and production (Aboyaji et al., 2019; Howeler, 2001). Potassium is also required for the initiation of cassava root growth and an increase in tuber size and number (Gonçalves et al., 2022). However, the observed decrease in tuber number, diameter, weight and yield with application of K beyond the optimum might be due to an imbalance in plant nutrition (Aboyaji et al., 2019; Gonçalves et al., 2022; Suminarti et al., 2022). Notably, when the soil already exhibited high K concentrations, a further increase in inorganic K application might not have any positive effect on tuber yield (Gonçalves et al., 2022). Excess K is said to restrict Mg and Ca absorption in the plant tissues, causing Mg and Ca deficiencies and affecting chlorophyll content, thus reducing the production and use of carbohydrates (Grzebisz et al., 2020; Suminarti et al., 2022). Potassium has also proven to have a positive effect on vegetative growth. This can be adduced to the fact that high rates of K enhances uptake of N thereby increasing vegetative growth, at the expense of tuber yield (Aboyaji et al., 2019; Gelaye et al., 2022).

2.4.5 Impact of compound NPK fertiliser on yield and yield components of root and tuber crops

The use of compound NPK fertilisers has been widely adopted because they supply all the three essential macronutrients, primary nutrients essential for plant growth and development. Application of compound fertiliser ensures an adequate and balanced supply of N, P and K for a well-developed plant canopy, high LAI, increased LAD, and increased physiological activities (Katuromunda et al., 2021). This was observed in cassava (Katuromunda et al., 2021; Munyahali et al., 2017; Mwamba et al., 2021) and potato (Sandhu et al., 2013; Santos et al., 2018). A balanced fertiliser application significantly increase tuber size, yield and quality. Thus, Tan et al. (2016) asserted that balanced NPK fertilisers are key to achieving the highest root and tuber yield targets. Furthermore, the application of compound NPK fertiliser increases the availability of nutrients required for physiological activities like photosynthetic activity, tuber formation and development, and tuber bulking (Katuromunda et al., 2021). That result in well-developed photosynthetic surfaces and increased physiological activities that are responsible for the production and translocation of more assimilates to the tubers. Furthermore, the application of a balanced NPK fertiliser also increases total leaf area and mean LAI, which

also increases the production, and uptake of photo-assimilates by the tubers (Mota *et al.*, 2020; Mozumder *et al.*, 2014). Thus, the positive response in tuber numbers per plant increased tuber weight and yield (Mwamba *et al.*, 2021; Sandhu *et al.*, 2013; Santos *et al.*, 2018). Conversely, Yagi *et al.* (2019) indicated that a further increase in NPK might cause a slight decrease in tuber yield depending on the formula of the NPK applied. The research showed that the application of NPK with more concentrated P should be preferred because it improves the efficiency of the potato planting operation.

2.4.6 Variations in RTC's response to the application of macronutrients and implications for further research

The systematic review indicated variations in tuber yield response to the application of inorganic NPK fertilisers. The variations ranged from positive, sigmoidal, and quadratic to negative responses to fertiliser application. These variations were significant in sweet potato and potato responses to the application of N, K and compound NPK. In studies that focused on the effect of inorganic N fertiliser on sweet potato, the findings by Duan *et al.* (2018) showed a reduction in tuber yield with increasing N application, while findings by Duan *et al.* (2019) showed a quadratic response, with optimal tuber yield at intermediate nitrogen levels. Another variation was observed in the response of sweet potato to the application of K. The findings by Aboyeji *et al.* (2019) reported a quadratic response whereas Wang *et al.* (2014) observed a significant increase in tuber yield till an asymptote was reached.

Similar variations were observed in potato with an application of N fertilisers. A significant increase in tuber yield was observed until an asymptote was reached in potato (Zebarth *et al.*, 2011). In contrast, a quadratic response to N fertiliser application was recorded by Yadav (Mozumder *et al.*, 2014; Yadav *et al.*, 2022). Similar trends were also observed with the application of K fertilisers. Grzebisz *et al.* (2020) reported a positive potato yield response to the application of K, whereas a sigmoidal response was observed in different research (Khan *et al.*, 2010; Yakimenko & Naumova, 2021). However, Haile (2011) reported a quadratic response to nitrogen application, with optimal tuber yield at intermediate nitrogen levels. These observed variations within species may be attributed to differences in environmental conditions, such as soil fertility, climatic conditions or management practices employed for the crop under study, such as plant spacing or experimental design (Sinta & Garo, 2021). These conflicting results underscore the need for site-specific research into the interaction between

N, P and K, and RTCs. Additionally, this highlights the need for site-specific and species-specific fertiliser recommendations for maximising RTC yield.

While significant research exists on the responses of crops like sweet potato and potato to macronutrient application, there is limited information on the nutrient requirements of *N. brachypus*. Given the observed variation in responses across species and within species, it is crucial to investigate how N, P, and K levels affect the growth and yield of *N. brachypus*. This will allow for the development of tailored fertiliser recommendations that maximise yield. Furthermore, as indicated by these variations, there is a need to investigate how management practices, such as plant spacing, affect mineral nutrient availability and use efficiency in *N. brachypus*.

2.4.7 Limitations of the study

In this systematic review, only English-written studies were included, so any other relevant non-English studies were not included. Grey literature and review papers were not included, only scientific papers were. These exclusions might have led to selection bias and, therefore, an underestimation of the overall effect of N, K, and P-based inorganic fertilisers on the growth components and yield of RTCs. A meta-analysis is needed in fertiliser assessment reviews to generate more robust recommendations for different RTC species' application rates. However, a greater percentage of the included studies had missing outcome data, and this made it challenging to conduct a meta-analysis.

The included publications had a bias in favour of potato, which may have skewed the conclusions towards potato production rather than the production of other root and tuber crop species. Another limitation was the experimental site, most of the experiments were carried out at research stations, which are often located on more fertile soils than the on-farm soil conditions (Haarhoff & Swanepoel, 2018). Furthermore, considering that studies that used and organic fertilisers were excluded from this study, a systematic review that takes organic fertilisers into account is recommended.

2.5 Conclusion

This systematic literature review has highlighted significant variations in the response of RTCs to the application of inorganic NPK fertilisers. The observed variations were attributed to

factors such as soil fertility, climatic conditions, and management practices, including plant spacing. These variations were observed both within species and also across different species. The variations ranged from no response, positive, sigmoidal, and quadratic to negative responses to fertiliser application. This underscores the need for tailored fertiliser application depending on the crop species and local conditions. Despite these inconsistencies, the review consistently identified N, P, and K as crucial for tuber development across RTCs, contributing to processes like photosynthesis, tuber bulking, and maturation. However, no previous studies were found for *N. brachypus*, which presents a significant research gap. Additionally, limited data on under-researched RTCs, such as Jerusalem artichoke, aquatic taro, and beetroot, made it difficult to draw concrete conclusions for these species. The variation in fertiliser responses, both within and across RTC species, highlights the need for site-specific and species-specific fertiliser recommendations. Exceeding optimal NPK levels may lead to diminishing returns or even a decrease in yield. The review findings indicate that a majority of studies applied rates between 0 to 300 kg/ha, with only three studies exploring application rates above 1 t/ha of compound NPK. This highlights a significant trend towards moderate fertiliser application, potentially reflecting a balance between crop nutrient demands and economic feasibility. This literature review underscores the importance of understanding the interrelationship between fertiliser application rates and other agronomic factors such as population density, and soil types. Given the lack of studies on *N. brachypus*, future research should focus not only on determining the effects of N, P, and K application but also on the influence of management practices such as plant spacing and population density. This research could provide valuable recommendations for optimising fertiliser use under varying environmental conditions.

CHAPTER 3: Effect of plant spatial arrangement and population density on tuber yield of *Neorautanenia brachypus* (Harms) C.A. Sm: Towards domestication

This chapter is based on an article under review in the African Journal of Rural Development as Kutamahufa, M. W., Murungweni, C., Chikwambi, Z. and Mashingaidze, A. B. Effect of plant spatial arrangement and population density on tuber yield of *Neorautanenia brachypus* (Harms) C.A. Sm: Towards domestication

Abstract

Adoption of a wild plant, *Neorautanenia brachypus* (Harms) CA. Sm. as a drought survival feed for livestock has recently increased in the south-eastern lowveld areas of Zimbabwe. Therefore, to facilitate domestication, a two-season study to determine the effect of plant spatial arrangement and plant population density on tuber yield at two sites with contrasting soil types sandy infertile soils (Zvimba) and deep fertile clays (Chikombedzi), was laid out in a randomised complete block design with treatments replicated three times. The factors were inter-row spacing (0.45, 0.60, and 0.75 m) and in-row spacing (0.30 and 0.45 m), leading to plant populations of 44444, 55555, 74074, 29629, 37037, and 49382 plants/ha. At the sandy infertile site with an annual rainfall of 882 mm, tuber length, diameter and yield were highest at the intermediate inter-row spacing (0.60 m) and were significantly lower at the narrow (0.45 m) and wide (0.75 m) inter-row spacing at 0.3 m in-row spacing. The highest tuber yield (1856 kg ha⁻¹) was recorded at 0.60 m inter-row × 0.30 m in-row with a plant population density of 55 555 plants ha⁻¹. In contrast, at the more fertile deep clay soil site with an annual rainfall of 540 mm, the narrow inter-row spacing (0.45 m) resulted in significantly higher ($P < 0.05$) tuber length (121.17 mm) and yield (2150 kg ha⁻¹) than the intermediate inter-row (0.6 m) spacing and the wide (0.75 m) inter-row spacing, averaged across in-row spacing. Tuber yield in the medium (0.60 m) and wide (0.75 m) inter-row spacing was about a third (739 kg ha⁻¹) and two-fifths (847 kg ha⁻¹) of the yield attained at the narrow row spacing (2150 kg ha⁻¹). However, there was no interaction between inter-row and in-row spacing on tuber yield. The results of this research showed that *N. brachypus*' tuber yield responses to spatial arrangement and population depended on soil fertility and climatic conditions. In the sandy less fertile soils, the 0.6 inter-row x 0.3 m in-row spatial arrangement maximised tuber yield, while in richly endowed soils, narrow inter-row spacing of 0.45 m was more effective. These results suggest that spatial arrangement and population density recommendations should be tailored to specific environmental conditions for optimal tuber production.

Keywords: Growth resources, in-row spacing, inter-row spacing, intra-specific competition, tuber yield

3.1 Introduction

Climate change poses a significant risk to agriculture, food, and nutrition security in the twenty-first century, particularly in many of Southern Africa's impoverished, agricultural-based

nations because of their limited capacity to cope (Nellemann, 2009; Shah et al., 2009). Climate change has led to an increase in dry regions at the expense of cropland, thereby increasing livestock production zones in countries such as Zimbabwe (Manyakaidze, 2023; Mugandani et al., 2012). The country has five agro-ecological zones, primarily categorised based on rainfall. Agro-ecological zones I to III are predominantly focused on crop production, whereas agro-ecological zones IV and V specialise in livestock production (Manyakaidze, 2023; Mugandani et al., 2012). However, livestock production in these zones is constrained by reduced forage production per unit area resulting in reduced forage availability during the dry season, this therefore increase the need for supplementary feed (Murungweni *et al.*, 2012; Oba, 2001). To reduce livestock production losses in the dry season, various strategies are being employed, including providing animals with hay, silage, and protein supplements. However, due to a lack of resources, knowledge and forage conservation skills, such strategies are out of reach for smallholder farmers in semi-arid regions of Zimbabwe (Balehegn *et al.*, 2022; Grey & Masunungure, 2020).

Nonetheless, in response to the dwindling livestock feed resources, farmers in the south-eastern lowveld areas of Zimbabwe located in agro-ecological zone V, have adopted a drought-resilient indigenous wild leguminous tuberous plant, (*Neorautanenia brachypus* (Harms) C.A. Sm.), as a drought survival feed (Murungweni *et al.*, 2012). The plant contains high quantities of crude protein and water, with a substantial amount of energy (Murungweni *et al.*, 2012). Furthermore, the plant also has anthelmintic and antibacterial properties (Mpofu *et al.*, 2022). *N. brachypus* has significant potential as an emergency relief feed due to its nutritional composition, which is adequate to meet the maintenance requirements of ruminant livestock during the dry season. Currently, farmers are harvesting *N. brachypus* tubers from the natural veld and cropping fields at random. To facilitate the domestication and sustainable use of *N. brachypus*, an evaluation of the agronomic requirements of the plant is needed. With the increasing dry spells and reduced rangeland productivity in semi-arid regions, facilitating commercial production of the crop will help alleviate livestock losses during droughts and dry seasons.

Among the agronomic practices that influence tuber growth and yield, plant spatial arrangement and population density are key to achieving high yields (Law-Ogbomo & Osaigbovo, 2014; Liu *et al.*, 2014). In potato, it has been reported that reducing row spacing and increasing population density results in low tuber yields per plant (de Almeida et al., 2016; Masarirambi et al., 2012). Zaimoglu Onat et al. (2017) indicated that increasing plant

population density per unit area would cause an increase in intraspecific plant competition for growth resources such as water, nutrients and light energy. Similarly, studies on cassava, taro, and sweet potato confirm that wider plant spacing and low plant density increase plant growth and tuber yield (Abd-Ellatif et al., 2010; Kumar et al., 2016; Meena et al., 2020). The increase in growth and yield might be attributed to less competition for growth resources, increased water uptake, reduced interplant shading of the crop and increased photosynthetically active radiation (PAR) interception (Meena et al., 2020; Zaimoglu Onat et al., 2017). At wider plant spacing, plants can produce enough leaf area to maximise radiation interception during reproductive growth, thereby increasing photosynthetic efficiency and maximising tuber yield. However, Arega, Tekalign, Solomon, & Tekile, (2018) observed that tuber numbers per unit of land area, increase at narrow plant spacing because of the high plant population density per unit of land. Likewise, in pulses, close plant spacing increases plant density per unit area and, as a result, increases pod yield per hectare (Zaimoglu Onat *et al.*, 2017). At narrow plant spacing and higher plant densities, the time taken for the canopy to attain full ground cover is reduced, and there is reduced interspecific plant competition with weeds. Due to this variation in response to different plant spacing between and within plant species, Zaimoglu Onat *et al.* (2017) concluded that it is important to establish an optimum plant population density per unit area of land to get the maximum yield for each plant species. Love and Thompson-Johns (1999) indicated that determining the plant row spacing at which optimum total yield occurred is the simplest approach to determine the optimum plant spatial arrangement and population density. Thus, considering the optimum inter-row and in-row spacing and plant densities is crucial to agronomists and farmers for maximisation of parameters of interest in newly domesticated plants (Zaimoglu Onat, Bakal, Gulluoglu, & Arioglu, 2017).

Effects of plant spatial arrangement and population density have been evaluated for major root and tuber crops (RTCs); however, no studies have yet addressed the subject of plant spatial arrangement and population density in the context of *N. brachypus* tuber growth and yield. The objective of this study was to determine the effect of plant spatial arrangement and plant population density on tuber yield at two sites with contrasting environments. The hypotheses tested were: (a) planting *N. brachypus* in narrow rows and increasing *N. brachypus* population density will decrease tuber growth and yield; (b) optimum spatial arrangement and population density depend on the availability of growth resources.

3.2 Materials and methods

3.2.1 Experimental location's description

The field experiments were carried out in 2020/21 and 2021/22 growing seasons under rain-fed conditions at two contrasting sites. Chikombedzi site in agro-ecological zone V on the dark clay eutric vertisols, a site that represents the dry areas of Zimbabwe where extensive livestock production is practised and Zvimba site in agro-ecological region IIb on granitic sandy arenosols, a site that represents the wet regions of Zimbabwe where intensive crop production is practised. Chikombedzi experimental site lies at 18° 05' 0.00" S, 29° 27' 0.00" E and an altitude of 400 m above sea level (Figure 3.1). Rainfall is highly variable in the area with an annual average of 400 mm falling between November and April and the average temperatures throughout the growing season are about 30 °C. Zvimba site lies at 17° 42' 0.00" S, 30° 12' 0.00" E and at an elevation of 1274 m above sea level (Figure 3.1). Zvimba communal area receives rainfall that ranges from 750 to 900 mm/year and the annual average temperature ranges from 22 to 26 °C.

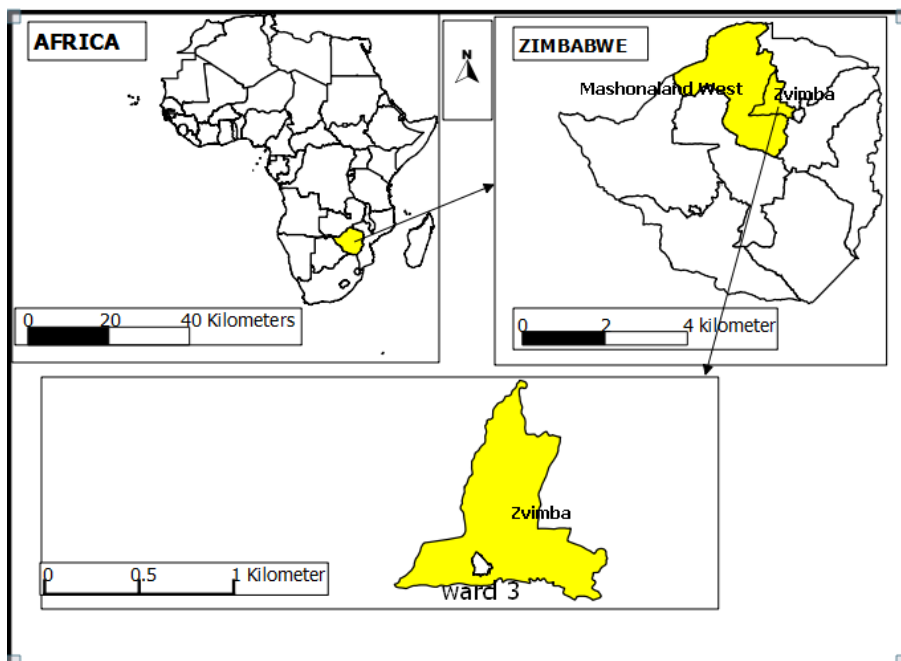
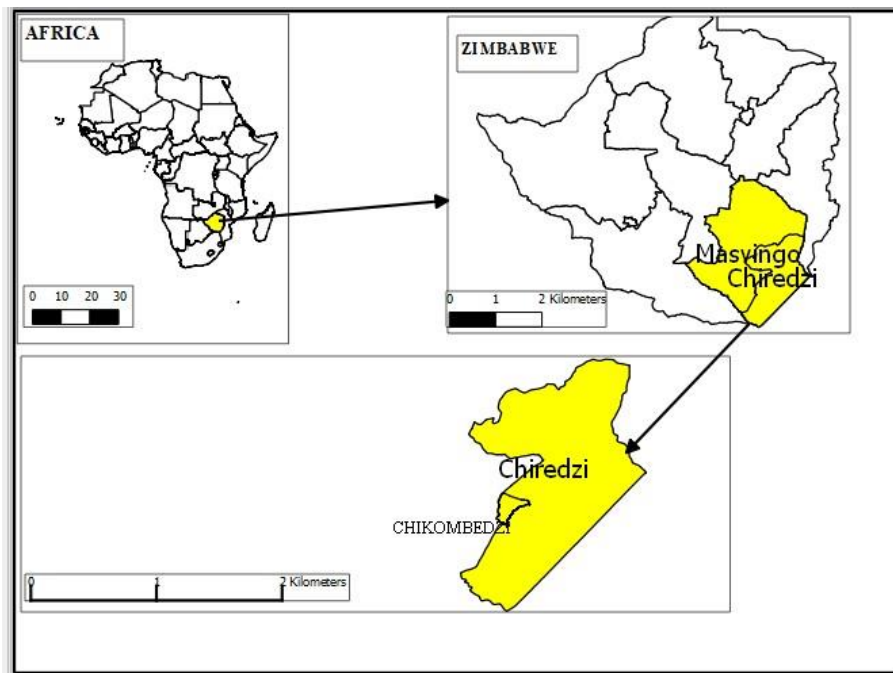


Figure 3.1: Maps of Africa showing the Chikombedzi study area in Chiredzi district and Ward 3 study area in Zvimba district in Zimbabwe.

3.2.2 Soil sampling and analysis

Soil samples were collected in December 2020 at both sites before the onset of the experiment. They were collected from 0-20 cm depth using a 0.20 m soil auger at 10 randomly selected points within each experimental site in a 0.40 ha field for detailed soil characterisation. The sub-samples were air-dried, crushed, sieved using a 2 mm sieve, and combined into four composite samples for each site. The samples were analysed for pH (0.01 M CaCl₂ method), initial mineral N (Kjeldahl method after extraction with 0.01 M KCl), and available P (Olsen method), the concentrations of K, and Mg were determined using Atomic Absorption Spectroscopy (AAS) following extraction with 1.0 M ammonium acetate at pH 5.8 (Table 3.1) (Anderson & Ingram, 1993; Gee & Bauder, 1986).

Table 3.1: Soil chemical properties on the onset of the experiment for Zvimba and Chikombedzi sites (General fertility interpretation range was adapted from Nyamangara, Mugwira, and Mpofu (2000) and Chitiga, Soropa, Dube, and Sengera (2023))

Soil parameter	Mean for Zvimba site sample	Mean for Chikombedzi site samples	Range	Fertility Interpretation range
Soil pH (0.01 M CaCl ₂)	4.37 ± 0.23	7.15 ± 0.56	<4.5	Very strong acid
			4.5 -5.0	Strong
			Above 5.0	Suitable for most
KCl-N after incubation (mg/kg)	12.5 ± 5	27.5 ± 9.57	Below 20	Very low

Resin-extractable P ₂ O ₅ (mg/kg)	1.21 ± 1.14	13.16 ± 3.48	20 – 30	Low
			Above 31	Medium to high
			Below 15	Deficient
			15 – 30	Marginal
			Above 30	Adequate to high
Exchangeable K (meq/100 g soil)	0.03 ± 0.01	0.835± 0.12	Below 0.45	Acutely deficient
			0.45 – 0.70	Deficient
			Above 0.70	Adequate to high
Exchangeable Mg (meq/100 g soil)	0.09 ± 0.02	14.69 ± 2.83	Below 0.10	Acutely deficient
			0.10 – 0.20	Deficient
			Above 0.20	Adequate to high

3.2.3 Experimental design, treatments and crop management

The first experimental factor was inter-row spacing (0.45, 0.60, and 0.75 m), and the second factor was in-row spacing (0.30, and 0.45 m). Leading to plant population densities of 44444, 55555, and 74074 plants ha⁻¹ for the narrow in-row (0.30 m) treatment combinations and 29629, 37037 and 49382 plants ha⁻¹ for the wide in-row (0.45 m) spacing treatment combinations. The experiment was laid out as a 3 × 2 factorial in a randomised complete block design (RCBD), with treatments replicated three times. The plots measured 5.5 m × 5.25 m, with 1.5 m wide pathways. The land was prepared to a fine tilth through ploughing and discing a day before planting. Planting holes were prepared using hand hoes and 150 kg ha⁻¹ of compound NPK fertiliser (7% N: 14% P₂O₅: 7% K₂O) was applied as basal fertiliser before seeding. Planting material (seeds) were harvested in the Chikombedzi area and the seeds were scarified using 100% sulphuric acid before planting. Planting of two seeds per planting station was done on December 28, 2020, and the seedlings were thinned to one seedling per planting station after emergence. Plants were left to grow for the two growing seasons because *N. brachypus* is a perennial plant. The crop was side-dressed at a rate of 75 kg ha⁻¹ of ammonium nitrate (AN, 34.5% N) at four weeks after emergence (WAE) for in the first growing season and at 57 WAE in the second growing season. Weeding was done manually using hand hoeing at four and eight WAE in the first growing season and at 57 WAE and 61 WAE in the second growing season.

3.2.4 Data collection

Yield parameters were measured at the end of the rainy season in April 2021 (17 WAE) and April 2022 (68 WAE) for the Zvimba site. For the Chikombedzi site yield parameters were measured once at the end of the two growing seasons in April 2022 (68 WAE). Five plants were randomly selected from each plot and carefully dug from the soil using garden spades, and the excess soil attached was shaken free and wiped off using a moist cloth. Tuber length and diameter were measured using a vernier calliper. Tuber fresh weight per plant was measured using a digital scale and converted to tuber fresh weight per hectare.

3.2.5 Data analysis

Residuals were tested for normality using Shapiro-Wilk's test (IBM SPSS Statistics Version 20). The homogeneity of residual variances was tested before ANOVA over years using Bartlett's test. Individual location and year analyses were done separately following Bartlett's

test. The year was considered a random factor, while inter-row spacing and in-row spacing were considered fixed factors. The data from the experiments were subjected to ANOVA using the Genstat Release 18th edition statistical package for Windows (VSN International, 2015). Where there were significant effects of treatments, means were separated using the $\pm$ standard error of difference ($\pm$ s.e.d.) at $P < 0.05$.

3.3 Results

3.3.1 Tuber length of *N. brachypus*

At the Zvimba site, there were significant interactions ($P < 0.05$) between inter-row and in-row spacing on tuber length in the 2020/21 and 2021/22 seasons (Table 3.2). Tuber length was 16% higher in the 0.3 m (narrow in-row spacing) than the 0.45 m (wide in-row spacing) at narrow inter-row spacing (0.45 m), in the the first growing season (2020/21, Figure 3.2a). However, tuber length was 18% lower in the 0.30 m than 0.45 m in-row spacing at medium inter-row spacing (0.60 m), and there was no significant difference in tuber length between the 0.30 m and 0.45 m in-row spacing at the widest inter-row spacing (0.75 m) in the first growing season (2020/21, Figure 3.2a). In the second season after planting (2021/22), at the same site, tuber length was 38% lower in the 0.30 m than 0.45 m in-row spacing at 0.45 m inter-row spacing (Figure 3.2b). However, under intermediate row spacing (0.6 m), tuber length was 17% higher in the 0.30 m than 0.45 m in-row spacing, and there was no significant effect of in-row at the widest inter-row spacing of 0.75 m in this second growing season (Figure 3.2b).

Table 3.2: Effect of inter-row and in-row spacing on *Neorautanenia brachypus* (Harms) C.A. Sm.) yield parameters in the 2020/21 and 2021/22 growing seasons at the Zvimba and Chikombedzi sites in Zimbabwe

	Murungweni Farm, Zvimba district						Zanamwe Farm, Chikombedzi district		
Inter-row spacing	Tuber length (mm)		Tuber diameter (mm)		Tuber yield (kg ha ⁻¹)		Tuber length (mm)	Tuber diameter (mm)	Tuber yield (kg ha ⁻¹)
	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22	2021/22	2021/22	2021/22
0.45 m	77.39 ^a	75.72 ^a	11.84 ^a	17.54 ^b	629.09 ^b	970.01 ^b	121.17 ^b	24.27 ^b	2150 ^b
0.60 m	77.57 ^a	105.88 ^b	17.36 ^b	18.96 ^c	422.40 ^a	1352.43 ^c	92.12 ^a	18.87 ^a	737 ^a
0.75 m	90.93 ^b	78.46 ^a	11.78 ^a	16.78 ^a	462.39 ^a	577.30 ^a	96.52 ^a	20.77 ^a	847 ^a
P-value	0.005	0.009	<.001	<.001	<.001	<.001	0.005	0.008	<.001
± sed	3.627	8.399	0.669	0.319	26.97	86.273	7.278	1.353	136.3
In-row spacing									
0.30 m	81.70	85.98	14.00	18.35 ^b	545.40 ^b	1221.38 ^b	96.60 ^a	19.94 ^a	1250
0.45 m	82.23	87.40	13.33	17.18 ^a	463.86 ^a	711.78 ^a	109.94 ^b	22.66 ^b	1239
P value	0.863	0.840	0.252	0.001	0.004	<.001	0.049	0.033	0.917
± sed	2.961	6.857	0.546	0.261	22.021	70.442	5.942	1.104	111.3
Inter-row spacing × In-row spacing interaction									
P value	0.024	0.014	0.864	<.001	0.161	0.002	0.042	0.613	0.182
± sed	5.129	11.877	0.946	0.452	38.141	122.009	10.292	1.913	192.8

*Note: Means followed by *same letter* superscripts within the same column are significantly different at $P < 0.05$

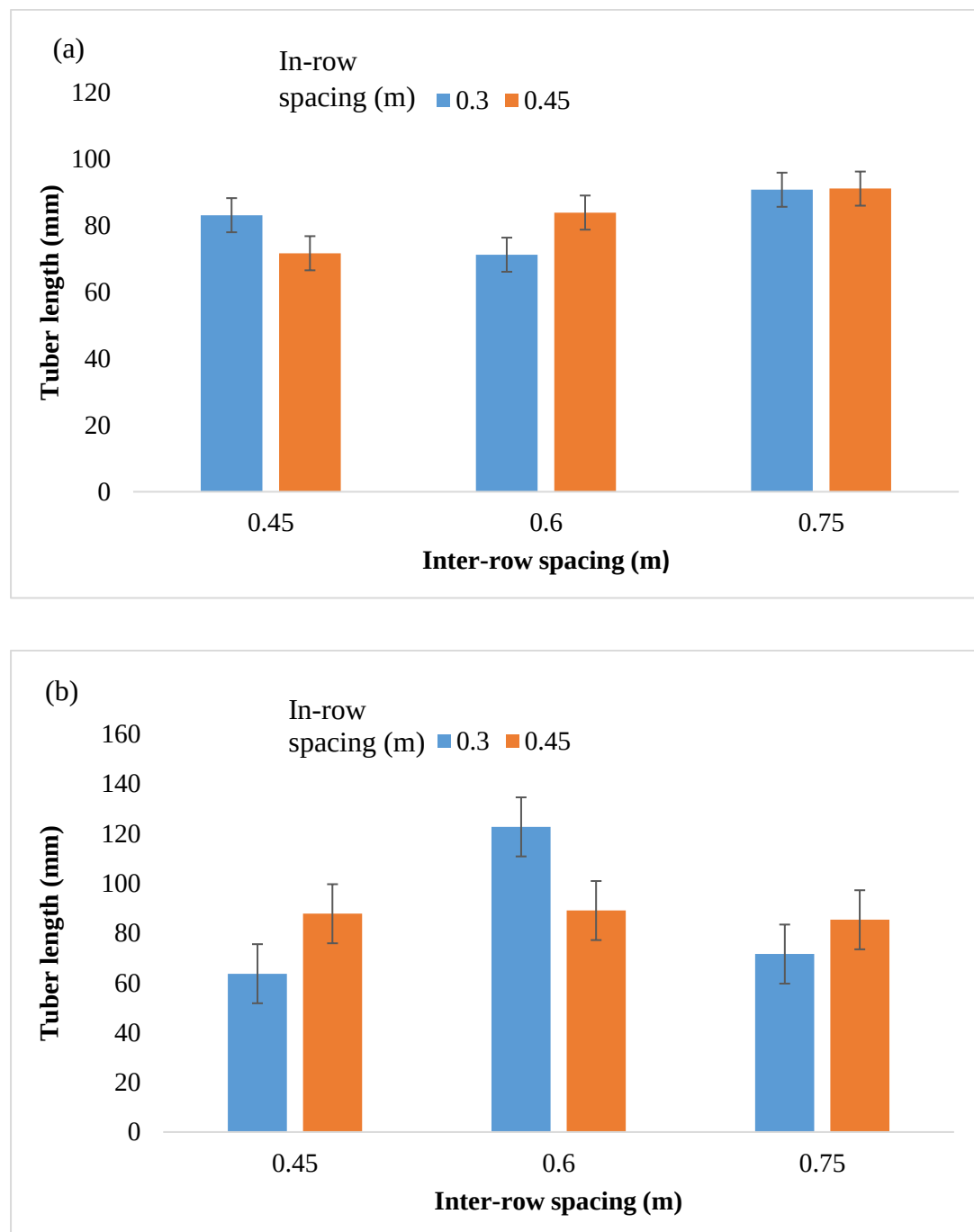


Figure 3.2: Interaction between inter-row spacing and in-row spacing on tuber length in the a) 2020/21 and b) 2021/22 growing seasons at the Zvimba site, Zimbabwe. (Error bars are $\pm$ standard error of difference ($\pm$ sed) for the comparison of in-row spacing means within and across inter-row spacing)

At the Chikombedzi site, tuber length was significantly influenced ($P < 0.05$) by inter-row spacing, in-row spacing and the interaction of the two factors (Table 3.2). Tuber length was higher by 36.9% and 26.6% lower in the 0.30 m than 0.45 m in-row spacing at 0.60 m and 0.75 m inter-row spacing, respectively (Figure 3.3). However, there was no significant difference in tuber yield between the 0.30 m and 0.45 m in-row spacing at the narrowest inter-row spacing of 0.45 m (Figure 3.3).

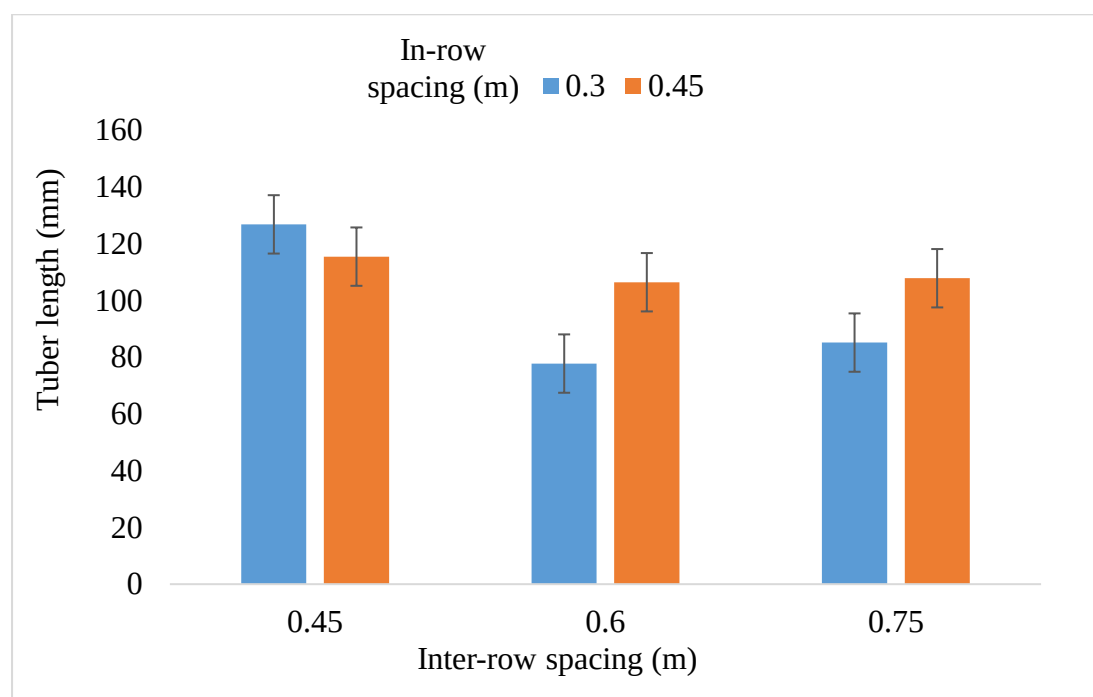


Figure 3.3: Interaction between inter-row spacing and in-row spacing on tuber length in 2021/22 growing seasons at the Chikombedzi site, Zimbabwe. (Error bars are $\pm$ standard error of difference ($\pm$ sed) for the comparison of in-row spacing means within and across inter-row spacing)

3.3.2 Tuber diameter of *N. brachypus*

The inter-row spacing significantly affected ($P < 0.05$) tuber diameter across both growing seasons at the Zvimba site (Table 3.2). Tuber diameter was higher at the medium inter-row spacing of 0.60 m and significantly decreased by 46.6% at the narrowest inter-row spacing and by 47.3% at the widest inter-row spacing in the 2020/21 season (Table 3.2). There was a significant interaction ($P < 0.05$) between inter-row and in-row spacing on tuber diameter in

the 2021/22 season (Table 1). Tuber diameter was 16.93% higher in the 0.30 m than 0.45 m in-row spacing at 0.60 m inter-row spacing, and there was no significant difference in tuber diameter between the 0.30 m and 0.45 m in-row spacing at the narrowest (0.45 m) and widest (0.75 m) inter-row spacing in the 2021/22 season (Figure 3.4).

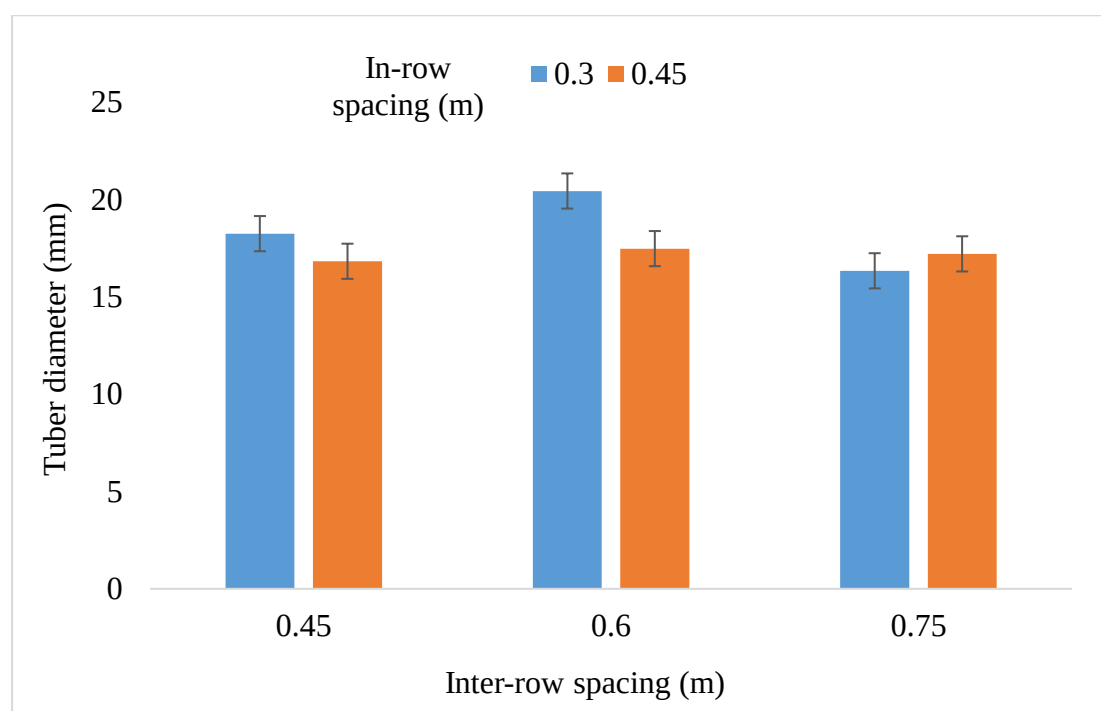


Figure 3.4: Interaction between inter-row spacing and in-row spacing on tuber diameter in 2021/22 growing seasons at the Zvimba site, Zimbabwe. (Error bars are $\pm$ standard error of difference ($\pm$ sed) for the comparison of in-row spacing means within and across inter-row spacing)

At the Chikombedzi site, tuber diameter was significantly influenced by both inter-row and by in-row spacing during the second growing season ($P < 0.05$, Table 3.2). Tuber diameter was higher under the narrowest inter-row spacing of 0.45 m and significantly decreased by 28.6% and 16.9% relative to the wider inter-row spacings of 0.60 m and 0.75 m, respectively, in the second growing season (Table 3.2). Tuber diameter was 13.6% higher when in-row spacing increased from 0.30 m to 0.45 m, averaged across the inter-row spacings (Table 3.2). However, there was no significant interaction ($P > 0.05$) between inter-row and in-row spacing on tuber diameter at the Chikombedzi site (Table 3.2).

3.3.3 Tuber yield of *N. brachypus*

Inter-row spacing significantly ($P < 0.05$) affected the tuber yield of *N. brachypus* at the Zvimba site in both growing seasons and at the Chikombedzi site (Table 3.2). Tuber yield was higher at the narrowest inter-row spacing (0.45 m) at the Zvimba site and was reduced by 36% and 49% when inter-row spacing was increased to 0.75 m and 0.60 m, respectively (Table 3.2). Similarly, tuber yield was higher at the narrowest inter-row spacing of 0.45 m at the Chikombedzi site and was 2.91 and 2.54 times lower at 0.75 m and 0.60 m inter-row spacing, respectively (Table 3.2). The effects of in-row spacing were significant on tuber yield at the Zvimba in both growing seasons ($P < 0.05$) and were not significant at the Chikombedzi site ($P > 0.05$). At the Zvimba site, tuber yield was 17.6% higher at 0.30 m than at 0.45 m in-row spacing in the 2020/21 season (Table 3.2). During the second growing season, there was a significant interaction ($P < 0.05$) between inter-row and in-row spacing on tuber yield at the Zvimba site (Table 3.2). Tuber yield was 42% and 118% higher in the 0.30 m than 0.45 m in-row spacing at inter-row spacings of 0.45 m and 0.60 m, respectively, and there was no significant difference in tuber yield between the 0.30 m and 0.45 m in-row spacing at the widest inter-row spacing of 0.75 m (Figure 3.5).

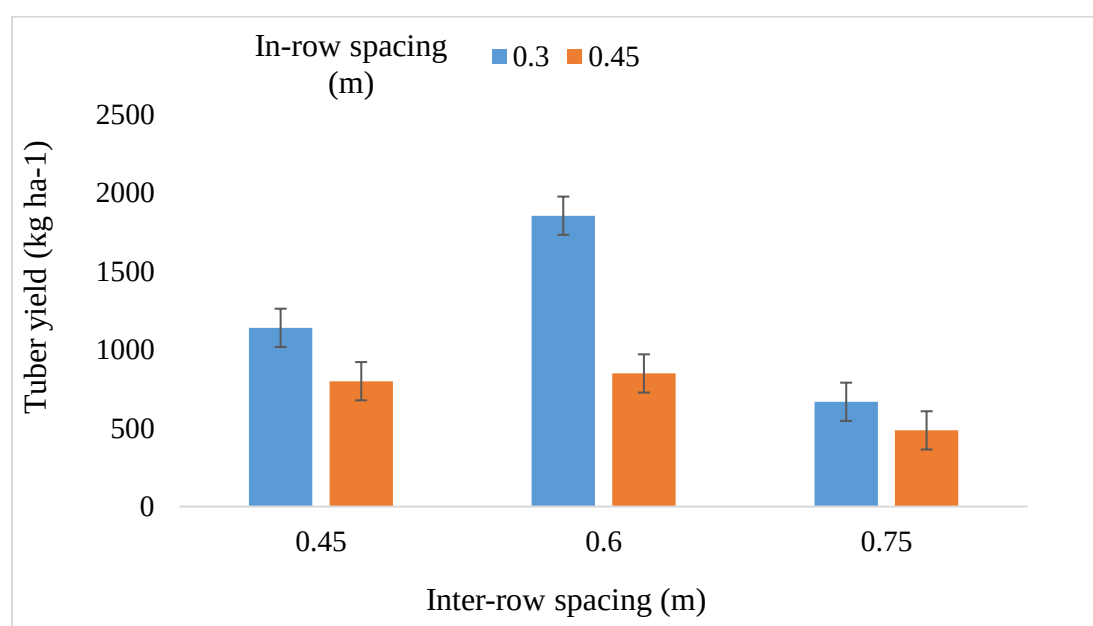


Figure 3.5: Interaction between inter-row spacing and in-row spacing on tuber yield in 2021/22 growing seasons at the Zvimba site, Zimbabwe. (Error bars are $\pm$ standard error of difference ($\pm$ sed) for the comparison of in-row spacing means within and across inter-row spacing)

3.4 Discussion

The study focused on the influence of plant spatial arrangement and population density on tuber yield and yield parameters of *N. brachypus* at two contrasting sites. The soil analysis results highlighted the contrasting fertility levels between Zvimba and Chikombedzi. Zvimba's soil pH of 4.37 was very strongly acidic, limiting nutrient availability, while Chikombedzi's pH of 7.15 was suitable for the productivity of most crops (Chitiga et al., 2023; Nyamangara et al., 2000). In terms of mineral nutrient composition, Zvimba's nitrogen (12.5 mg/kg) and phosphorus (1.21 mg/kg) levels were very low, compared to Chikombedzi's higher nitrogen (27.5 mg/kg) and phosphorus (13.16 mg/kg). Potassium and magnesium levels at Zvimba are acutely deficient (0.03 and 0.09 meq/100 g, respectively), whereas Chikombedzi shows adequate levels (0.835 and 14.69 meq/100 g). These results confirm Zvimba as a low-fertility site and Chikombedzi as a higher-fertility site (Chitiga et al., 2023; Nyamangara et al., 2000).

The results indicated that inter-row spacing had a significant impact on the *N. brachypus* tuber diameter and yield at both sites in the arenosols of Zvimba and the eutric vertisols of Chikombedzi. The high yields recorded at the Zvimba site in the intermediate inter-row spacing may potentially indicate low intraspecific competition for growth resources in the first growing season (Mohler et al., 2001). At the high soil fertility site (Chikombedzi), the high yields recorded in the narrower inter-row spacing suggest the availability of growth resources in high soil fertility environments; therefore, there is low intraspecific competition at narrow inter-row spacing. The high yields at the narrowest inter-row spacing can also be attributed to early canopy closure and, therefore, increased radiation interception, photosynthesis rate and allometric allocation of assimilates to economic yield (Arega et al., 2018; Fanadzo et al., 2010).

The results also indicated that, under low soil fertility, reducing in-row spacing from 0.45 m to 0.30 m resulted in an increment in tuber yield in the first growing season. This was also observed in potato by Masarirambi *et al.* (2012), in taro (Abd-Ellatif *et al.*, 2010), and in sweet potato (Wees et al., 2016). At high soil fertility, tuber diameter was highest at 0.45 m, the widest in-row spacing. This might be attributed to adequate space for root and tuber expansion as well as the fact that more nutrients are available for tuber development (Szarvas et al., 2018). Similarly, Demisie and Tolessa (2018) discovered that bulb length in onions increased with an increase in in-row spacing. They attributed the increase in bulb length to increased vegetative growth at wide spacing and increased surface area for radiation interception, which will favour a high photosynthetic rate and the accumulation of carbohydrate in onion bulbs (Demisie &

Tolessa, 2018; Meena *et al.*, 2020). These results reinforce the observation that at wider in-row spacing, there is reduced intraspecific competition for growth resources, which allows roots and tubers to have more assimilates available for storage (Arega *et al.*, 2018; Demisie & Tolessa, 2018). In sweet potato, it was discovered that plants with wide spacing have stronger stems than those with narrow spacing; these can support more branches and leaves, thus providing more surface area for light interception and an increased photosynthetic rate (Meena *et al.*, 2020; Wees *et al.*, 2016).

Furthermore, the findings of this study indicated that the optimal spatial arrangement and population density might vary depending on soil fertility levels or environmental conditions. At a high rainfall and low fertility arenosol sandy soil (Zvimba site), there was a significant interaction between inter-row and in-row spacing on all parameters while at a low rainfall and high fertility eutric vertisol (Chikombedzi site), it was on tuber length only. This implies the importance of adopting optimum inter-row and in-row spacing for the production of *N. brachypus* which is specific to the particular agro-ecological zone and soil fertility status.

In this study, the interaction effects observed for tuber yield were similar to those recorded for tuber size parameters (length and diameter), indicating that the effects of spatial arrangement on yield were primarily expressed through its influence on tuber length and diameter. In the low fertility arenosol sandy soil, in the second growing season, yield performance (kg ha^{-1}) was greatest at the highest plant density levels at 0.6 m inter-row x 0.3 m in-row spacing (55 555 plants ha^{-1}) and 0.45 m inter-row x 0.3 m in-row spacing (74 074 plants ha^{-1}). This might be attributed to early canopy cover at high plant densities and increased radiation interception for assimilation, thus the early initiation of tuber growth (Osaigbove *et al.*, 2016; Tsedalu *et al.*, 2014). In other perennial RTCs, tuber initiation and growth are determined in the first phase of plant growth (Abd-Ellatif *et al.*, 2010; Osaigbove *et al.*, 2016). Therefore, early canopy closure entails better utilisation of growth resources and high photosynthetic efficiency, which leads to an increase in tuber size and tuber yields. This implies that high population density and narrow spatial arrangement are suitable for adoption by farmers for *N. brachypus* production. In previous studies, the high yields were attributed to reduced interspecific competition from weeds (Song *et al.*, 2020; Tsedalu *et al.*, 2014). High plant densities reduced the time taken to cover the entire ground, thereby suppressing weeds (Wees *et al.*, 2016). This reduces below-ground competition for nutrients in the inner row spaces, hence increasing tuber growth (de Almeida *et al.*, 2016). This is contrary to the views of Muoneke *et al.* (2007) and Arega *et al.*

(2018) that in higher plant densities there is increased competition for light and other resources, which decreases the availability of nutrients to each plant and consequently results in lower plant biomass and yields. Ultimately, the lower tuber yield and size recorded in wide spatial arrangements (0.75 inter-row x 0.45 m in-row and 0.60 m inter-row x 0.45 m in-row) may be due to the lower population densities of *N. brachypus* per unit area of 29 629 and 37 037 plants ha⁻¹ (respectively) rather than to intraspecific plant competition (Ogbonna et al., 2015; Osaigbove et al., 2016). Zaimoglu Onat et al. (2017) reported that peanut yield increases with an increase in plant population density. This might as well imply that at lower *N. brachypus* plant densities (29629 and 37037), there is a reduced number of tubers being harvested per unit area of land.

In addition, the impact of row spacings on plant responses can be affected by various stresses, such as extreme temperatures, competition from weeds, water scarcity, and compacted soil. As demonstrated by previous studies, these stresses can limit leaf area expansion and radiation use efficiency, ultimately impacting tuber yield and diameter (Abd-Ellatif *et al.*, 2010; Kumar *et al.*, 2016). The findings are consistent with this, as it was observed that the rainfall patterns in Zvimba and Chikombedzi contributed to the *N. brachypus* tuber yield response to plant spacing and density. The interaction between inter-row and in-row spacing had a significant effect on tuber yield and diameter at the Zvimba site, where a high annual rainfall of 882 mm was recorded. This suggests that the adequate rainfall at the Zvimba site further supports the second most dense plant population of 55 555 at 0.60 m inter-row x 0.3 m in-row spacing, ensuring adequate moisture for optimal tuber growth even in less fertile soils. On the other hand, at the Chikombedzi site, the interaction between inter-row and in-row spacing was not significant on tuber yield and diameter, this should hold given an annual rainfall of 540 mm.

3.5 Conclusion and Recommendations

The study showed that plant spatial arrangement and population density significantly affected *N. brachypus* tuber yield in contrasting environments. In sandy soils with higher rainfall (Zvimba site), an interaction of 0.6 m inter-row and 0.3 m in-row spacing with a plant population density of 55555 plants ha⁻¹ maximised yield, while in more fertile soils with lower rainfall (Chikombedzi site), narrower inter-row spacing (0.45 m) was more effective. These results suggest that recommendations should be tailored to specific soil fertility status and annual rainfall amount for optimal tuber production. Furthermore, from a domestication perspective, it is important to determine the optimal spatial arrangement and plant population

that will maximise tuber yield across multiple growing seasons, whether harvested after one, two, three, or more seasons. Additionally, the optimisation of plant spacing should be explored further in areas with shorter growing seasons and lower total rainfall.

CHAPTER 4: Nitrogen, phosphorus and nitrogen mineral nutrients, compound NPK and AN influence tuber growth and yield of *Neorautanenia brachypus* (Harms) CA. Sm.

Abstract

Neorautanenia brachypus (Harms) C.A. Sm. is a tuberous plant whose ethnoveterinary importance and feed value have recently been established, necessitating its domestication. This study aimed to generate recommendation domains of the type of fertiliser and compound nitrogen (N), phosphorus (P) and potassium (K) and N top dressing fertiliser application rates for *N. brachypus* in two related experiments. The two field experiments were carried out in the 2020/21 and 2021/22 growing seasons at two contrasting sites: at a low rainfall, the Chikombedzi site with eutric vertisols, and at a high rainfall, Zvimba site with arenosols. The first experiment was laid out in a randomised complete block design (RCBD) with eight treatments (0 kg ha⁻¹ fertiliser; 145 kg ha⁻¹ N; 128 kg ha⁻¹ P₂O₅; 121 kg ha⁻¹ K₂O; 145 kg ha⁻¹ N + 128 kg ha⁻¹ P₂O₅; 145 kg ha⁻¹ N + 121 kg ha⁻¹ K₂O; 128 kg ha⁻¹ P₂O₅ + 121 kg ha⁻¹ K₂O; and 145 kg ha⁻¹ N + 128 kg ha⁻¹ P₂O₅ + 121 kg ha⁻¹ K₂O;) replicated three times. The second experiment was a 4 x 4 factorial in an RCBD with sixteen treatments and three replicates from four compound NPK (7% N: 14% P₂O₅: 7% K₂O) by four ammonium nitrate (AN, 34.5% N) fertiliser rates (0 kg ha⁻¹, 75 kg ha⁻¹, 150 kg ha⁻¹, 300 kg ha⁻¹) factorial combinations. The research findings showed no significant difference between N, P, & K macronutrients as straight fertilisers, their combination, and the control treatment, where no fertiliser was applied except for the 145 kg ha⁻¹ N treatment. Application of 145 kg ha⁻¹ N significantly reduced tuber yield (**P** < 0.05) by 63% and 62.5% at the Zvimba and the Chikombedzi site, respectively, compared to the control. Application of 128 kg ha⁻¹ P₂O₅ increased yield by 34% compared to the control treatment at the Chikombedzi site. This effect was also recorded for tuber length, showing that the effects of individual macronutrients on tuber yield were expressed through the impact of these treatments on tuber length. In the second experiment, there was a highly significant interaction (**P** < 0.05) between compound NPK and AN fertiliser application rates, at both sites on *N. brachypus* tuber yield. At the sandy arenosol Zvimba site, the application of 0 kg ha⁻¹ compound NPK + 75 kg ha⁻¹ AN and 150 kg ha⁻¹ compound NPK + 150 kg ha⁻¹ AN achieved higher tuber yields than the control treatment in the 2021/22 growing season. At the clay eutric vertisol Chikombedzi site, 150 kg ha⁻¹ compound NPK + 150 kg ha⁻¹ AN and 75 kg ha⁻¹ compound NPK + 300 kg ha⁻¹ AN resulted in a higher tuber yield than the control treatment. However, the interactions did not show a clear trend of how *N. brachypus* yield responded to

combinations of basal NPK application plus AN top-dressing fertiliser. Therefore, more research is needed to understand the compound NPK and N-top dressing fertiliser requirements of *N. brachypus*, which, like other wild root and tuber crops, showed that it may require little or no fertiliser.

Keywords

Compound NPK fertilisers, fertiliser application rates; *Neorautanenia brachypus*, straight NPK fertilisers, tuber size and yield

4.1 Introduction

In terms of worldwide carbohydrate supplies, root and tuber crops (RTCs) are second only to grain cereals, with approximately 237 metric tonnes of global production between 2018 and 2020 (Chandrasekara and Josheph Kumar, 2016). They produce a significant portion of the world's animal feed and processed goods for human consumption and industrial usage (Chandrasekara and Josheph Kumar, 2016, Dhliwayo, 2002). These RTCs are significant sources of valuable chemical compounds that have antioxidant, antibacterial, and hypocholesterolemic effects, among others (Nanbol and Namo, 2019).

One of these RTCs with a high potential for medicinal use is *Neorautanenia brachypus* (Harms) C.A. Sm, a deciduous sub-erect, climbing, or occasionally prostrate perennial herb from the Leguminosae-Papilionaceae family (Hyde, 2014). Murungweni *et al.* (2012) reported that the tuberous root of *N. brachypus* has been adopted by many farmers in the south-eastern Lowveld of Zimbabwe as a drought-mitigating feed for ruminant livestock. This tuberous root has adequate nutrients to meet the maintenance requirements of ruminant livestock during drought (Murungweni *et al.*, 2012). In addition to its nutrient status as a feed supplement, *N. brachypus* has been used as a dewormer and an antibiotic by farmers in the south-eastern lowveld area of Zimbabwe (Murungweni *et al.*, 2014). Murungweni *et al.* (2012) demonstrated the anthelmintic potential of this tuberous root on infected goats and cattle. *N. brachypus* fed goats and cattle had significantly fewer worm infections than those not fed on the tuber, and *N. brachypus* reduced worm infections similarly to commercially available anthelmintic drugs on the market.

The plant is recognised in the south-eastern lowveld in Zimbabwe as one of the salient species for use in the preparation of medicinal remedies for treating various ailments for the human population, and veterinary remedies and feed for animals (Mero Dowo, Kativu, & de Garine-Wichatitsky, 2018). As a result, several farmers in Zimbabwe's Chikombedzi region have begun to plant *N. brachypus* in their farmyards, aiming for its domestication as a new crop. Domestication is defined as a genetic selection process exerted, consciously or unconsciously, by humans to adapt wild plants and animals to cultivation and herding, respectively (Gepts & Papa, 2003). Being a legume, *N. brachypus* has hard seeds that require breaching of the seed coat through weathering by the environmental factors or by chemicals before they germinate (Smýkal, Vernoud, Blair, Soukup, & Thompson, 2014). Tauro *et al.* (2019) showed that physical and acid scarification could break the physical dormancy caused by hard seed coats in *N. brachypus* seeds. Pisa *et al.* (2022) determined that ridging and application of phosphatic fertilisers increased *N. brachypus* growth rate. However, there is no information on *N. brachypus* mineral nutrient and fertiliser requirements to enable its domestication.

Carbohydrate yielding plants, such as African yam bean, cassava, and potato, require N and P for growth, and K for starch accumulation (Oliveira *et al.*, 2017, Adewale and Odoh, 2013). According to Oliveira *et al.* (2020), the application of inorganic fertilisers such as N, P, and K enhances potato tuber yield in terms of size and weight. Notably, the production of tropical and subtropical RTCs requires adequate compound NPK fertilisers for high attainable yields and the production of high-quality tubers (Bhardwaj *et al.*, 2021, Liu *et al.*, 2014). Different species of RTCs have different mineral nutrient requirements, and this is also environment dependent (Liu *et al.*, 2014, Duque and Villordon, 2019). Research on RTC's yield response to NPK inorganic fertilisers indicated that there is an optimum range of application rates that can maximise tuber yield. Beyond this range, diminishing returns in tuber growth and yield were observed in potato (Zebarth *et al.*, 2011, Mozumder *et al.*, 2014, Nurmanov *et al.*, 2019), sweet potato (Wang *et al.*, 2014, Munda *et al.*, 2019, Luz *et al.*, 2013), and cassava (Mota *et al.*, 2020, Katurumunda *et al.*, 2021). In other instances, higher application rates beyond the optimum had a negative impact on tuberous root yields. This results in a decline in the tuber yield of RTCs at high NPK application rates (Aboyaji *et al.*, 2019, Gonçalves *et al.*, 2022, Noor *et al.*, 2015, Sinta and Garo, 2021). Mineral nutrient requirements are also cultivar dependent, and fertiliser-susceptible cultivars might respond negatively to the application of NPK inorganic fertilisers. This was observed in the tuber yield and tuber number of sweet potato that were evaluated for nitrogen-susceptibility (Duan *et al.*, 2018, Duan *et al.*, 2019). However, to date,

there has been limited research on the effects of P fertiliser on *N. brachypus* growth and tuber yield. One of these studies has reported the benefits of fertiliser application to tuber length (Pisa *et al.*, 2022). Currently, it appears there are no studies have been conducted on the effect of the rate of application of compound NPK fertiliser and N top dressing fertiliser on *N. brachypus* growth and yield. This information is important to generate recommendation domains of the type of fertiliser and compound NPK and N top dressing fertiliser application rates for *N. brachypus* in facilitating the domestication and adoption of *N. brachypus* as a crop. This study aimed to generate recommendation domains of the type of fertiliser and compound nitrogen (N), phosphorus (P) and potassium (K) and N top dressing fertiliser application rates for *N. brachypus* in two related experiments. The first objective of this study was to determine, using a nutrient omission design, the effects of 145 kg ha⁻¹ N, 128 kg ha⁻¹ P₂O₅ and 121 kg ha⁻¹ K₂O straight fertilisers and their combinations (N & P, N & K, P & K and N, P & K) on the growth and yield of *N. brachypus*. The second objective was to determine the effects of compound NPK fertiliser and N top-dressing fertiliser on the growth and tuber yield during the early growth of *N. brachypus*. The results of this study will contribute information on mineral nutrient requirements and fertiliser recommendations for *N. brachypus* under smallholder farming conditions to facilitate its domestication.

4.2 Materials and Methods

4.2.1 Description of Experimental Sites

Experiments on the effect of NPK fertilisers on *N. brachypus* were carried out over a two-season period from the 2020/21 to 2021/22 growing seasons under rain-fed conditions at Murungweni farm (Zvimba site) and Zanamwe farm (Chikombedzi site). The Zvimba experimental site lies at 17° 42' 0.00" S, 30° 12' 0.00" E and at an altitude of 1274 m, on sandy loam arenosol soils with a pH of 4.37, total N of 12.5 mg kg⁻¹ (Kjeldahl method) and available P content of 1.21 mg kg⁻¹ P₂O₅ (Olsen method). The average annual rainfall of the area is 750 to 900 mm, which falls between November and April. Daily average temperatures during the growing season range from 22 to 26 °C. The Chikombedzi experimental site lies at 18° 05' 0.00" S, 29° 27' 0.00" E and at an altitude of 600 m, on dark clay eutric vertisol soils with a pH of 7.15, total N of 27.5 mg kg⁻¹ (Kjeldahl method), and an available P of 13.16 mg kg⁻¹ P₂O₅ (Olsen method). Rainfall is highly variable in the area, with a mean annual rainfall of 400 mm falling between December and March. The mean maximum temperature in that region is about 35 °C and the mean minimum temperature is about 15 °C.

4.2.2 Experimental design and layout

Experiment 1

The experiment was laid in a randomised complete block design (RCBD) with three replicates. The experiment consisted of eight treatments that were randomly allocated to eight plots in each replication. The treatments were 145 kg ha⁻¹ N, 128 kg ha⁻¹ P₂O₅ and 121 kg ha⁻¹ K₂O straight fertilisers and their combinations: 145 kg ha⁻¹ N + 128 kg ha⁻¹ P₂O₅ (NP); 145 kg ha⁻¹ N + 121 kg ha⁻¹ K₂O (NK); 128 kg ha⁻¹ P₂O₅ + 121 kg ha⁻¹ K₂O (PK); 145 kg ha⁻¹ N + 128 kg ha⁻¹ P₂O₅ + 121 kg ha⁻¹ K₂O (NPK); and negative control of 0 kg ha⁻¹ fertiliser. As a result, the total number of experimental units was 24 plots. The experimental plots measured 5.5 m × 5 m with a 1.5 m pathway between two replications and a one m pathway between two plots within the same replication.

Experiment 2

The experimental design was a 4 × 4 factorial in an RCBD with three replicates. Factor one comprised four NPK fertiliser (7% N:14% P:7% K) application rates: 0 kg ha⁻¹, 75 kg ha⁻¹, 150 kg ha⁻¹ and 300 kg ha⁻¹. These four compound NPK fertiliser application rates were combined with four ammonium nitrate (AN, 34.5% N) fertiliser application rates (0 kg ha⁻¹, 75 kg ha⁻¹, 150 kg ha⁻¹ and 300 kg ha⁻¹). As a result, 16 treatments were replicated three times for a total of 48 plots. The compound NPK fertiliser was applied at planting as basal fertiliser and the N top dressing AN fertiliser was applied at 4 weeks after emergence. The experimental plots measured 5.5 m × 5 m with a 1.5 m pathway between two blocks and a 1 m pathway between two plots within the same block.

4.2.3 Field operations and crop management

For all the experiments, the land was prepared to a fine tilth by an ox-drawn plough a day before planting. Two acid-scarified seeds of *N. brachypus* were planted per station at 0.60 m inter-row × 0.45 m in-row spacing and thinned to one plant two weeks after emergence living a plant population of 37 37 plants ha⁻¹. Planting was done on the 28th of December 2020 at the Chikombedzi site and on the 6th of January 2021 at the Zvimba site. Plant growth was observed over two growing seasons to capture at least two developmental cycles of the *N. brachypus* plant. At four weeks after emergence (WAE), in the first experiment, the crop was side-dressed

with AN according to treatments. Weeding was done manually using hand hoeing twice a season for each site at four and eight WAE and in the first growing season. In the second growing season, weeding was done at 57 WAE and 61 WAE.

4.2.4 Data collection

For all experiments, yield parameters were measured at the end of the rainy season in April 2021 (17 WAE) and April 2022 (68 WAE) for the Zvimba site. However, for the Chikombedzi site yield parameters were measured once at the end of the two growing seasons in April 2022 (68 WAE). For each plot, five plants were selected at random, carefully dug from the soil, and cleaned of excess soil by shaking and wiping off with a damp cloth. Tuber length and diameter were measured using a vernier calliper. The fresh tuber weight per plant was measured using a digital scale and converted to fresh tuber yield per hectare (kg ha^{-1}).

4.2.5 Data analysis

Residuals were tested for normality using Shapiro-Wilk's test (IBM SPSS Statistics Version 20). Homogeneity of residual variances was tested prior to ANOVA over years using Bartlett's test. Individual location and year analyses were done separately following Bartlett's test. Year and replications were considered as random factors, while straight fertilisers and their combination were considered as fixed factors for the first experiment. For the the second experiment, compound NPK and N-top dressing fertiliser were considered as fixed factors. All data was subjected to analysis of variance (ANOVA) using the Genstat Release 18th edition statistical package (VSN International, 2015). Standard errors of difference ($\pm \text{sed}$) were used for mean separation when treatment effects were significant at $P < 0.05$. Plus/minus standard error of the difference bars are shown in the charts.

4.3 Results

4.3.1 *Neorautanenia brachypus* tuber length

Experiment 1: Effect of N, P and K macronutrients and their combinations on N. brachypus' tuber length

Fertiliser treatments significantly affected ($P < 0.05$) tuber length at the Zvimba site in the 2020/21 and 2021/22 seasons (Table 4.1). There was no significant difference in tuber length between the control treatment and all other fertiliser treatments, except for the $128 \text{ kg ha}^{-1} \text{ P}_2\text{O}_5$

+ 121 kg ha⁻¹ K₂O treatment that recorded the lowest tuber length in the 2020/21 season at the Zvimba site (Table 4.1). Tuber length did not significantly differ between the control and all fertiliser treatments except for 121 kg ha⁻¹ K₂O treatment which increased tuber length by 22% and the 145 kg ha⁻¹ N treatment which reduced tuber length by 16% compared to the control at the Zvimba site in the 2021/2022 season (Table 4.1). At the Chikombedzi site, in the second season after planting (2021/2022), there was no significant difference ($P > 0.05$) in tuber length between the control and all fertiliser treatments except for the 128 kg ha⁻¹ P₂O₅ treatment which increased tuber length by 32% and the 145 kg ha⁻¹ N which reduced tuber length by 22% compared to the control (Table 4.1).

Experiment 2: Effect of compound NPK and AN fertiliser application rates on N. brachypus tuber length

Compound NPK fertiliser treatments significantly affected ($P < 0.05$) tuber length of *N. brachypus* at the Zvimba site in the 2020/21 season (Table 4.2). There was no significant difference in tuber length between the control treatment and all other compound NPK fertiliser treatments, except for the 300 kg ha⁻¹ compound NPK treatment, which reduced tuber length by 21.09% compared to the control (Table 4.2). The effects of AN fertiliser were not significant ($P > 0.05$) on tuber length at the Zvimba site in the 2020/21 growing season (Table 4.2).

Table 4.1: Effect of N, P and K macronutrients and their combinations on *Neorautanenia brachypus* (Harms) C.A. Sm yield parameters in the 2020/21 and 2021/22 growing seasons at the Zvimba and Chikombedzi sites

	Murungweni Farm, Zvimba site						Zanamwe Farm, Chikombedzi site		
Fertiliser Treatments	Tuber length (mm)		Tuber diameter (mm)		Tuber yield (kg ha ⁻¹)		Tuber length (mm)	Tuber diameter (mm)	Tuber yield (kg ha ⁻¹)
	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22	2021/22	2021/22	2021/22
0 kg ha ⁻¹	65.92 ^b	119.44 ^b	11.77 ^{bc}	21 ^b	259.8 ^{cd}	856 ^b	79.54 ^b	17.76 ^a	551.78 ^c
145 kg ha ⁻¹ N	52.71 ^b	100.02 ^a	9.34 ^b	18.96 ^{ab}	177.8 ^b	522 ^a	62.1 ^a	19.81 ^{ab}	339.01 ^a
128 kg ha ⁻¹ P ₂ O ₅	53.75 ^b	126.89 ^b	10.65 ^{bc}	21.81 ^b	194.6 ^{bc}	993 ^b	104.76 ^c	19.87 ^{ab}	734.44 ^d
121 kg ha ⁻¹ K ₂ O	72.6 ^b	145.97 ^c	9.97 ^{bc}	22.25 ^b	316.6 ^{cd}	807 ^b	90.6 ^{bc}	21.09 ^b	612.34 ^c
145 kg ha ⁻¹ N + 128 kg ha ⁻¹ P ₂ O ₅	73.72 ^b	108.53 ^{ab}	13.48 ^c	22.05 ^b	336.5 ^d	959 ^b	84.77 ^b	23.95 ^b	490.03 ^{bc}
145 kg ha ⁻¹ N + 121 kg ha ⁻¹ K ₂ O	61.49 ^b	110.78 ^{ab}	12.34 ^c	16.73 ^a	353.9 ^d	651 ^{ab}	79.6 ^b	17.31 ^a	453.58 ^b
128 kg ha ⁻¹ P ₂ O ₅ + 121 kg ha ⁻¹ K ₂ O	22.5 ^a	126.78 ^b	5.31 ^a	20.27 ^b	55.7 ^a	702 ^{ab}	77.68 ^b	21.75 ^b	639.61 ^c
145 kg ha ⁻¹ N + 128 kg ha ⁻¹ P ₂ O ₅ : 121 kg ha ⁻¹ K ₂ O	57.71 ^b	121.57 ^b	10.86 ^{bc}	20.53 ^b	257.2 ^c	718 ^{ab}	90.5 ^{bc}	21.94 ^b	528.74 ^{bc}
P-value	0.01	0.006	<.001	0.004	<.001	0.038	0.005	0.017	<.001
± sed	11.134	8.987	1.323	1.143	39.13	129.4	7.762	1.619	44.026

*Note: Means followed by *same letter* superscripts within the same column are significantly different at P<0.05

Table 4.2: Effect of compound NPK (7% N:14% P:7% K) and AN (34.5% N) fertiliser on *Neorautanenia brachypus* (Harms) C.A. Sm yield parameters in the 2020/21 and 2021/22 growing seasons at the Zvimba and Chikomedzi sites

	Murungweni Farm, Zvimba district						Zenamwe Farm, Chikomedzi district		
compound NPK Fertiliser (7:14:7)	Tuber length (mm)		Tuber diameter (mm)		Tuber yield (kg ha ⁻¹)		Tuber length (mm)	Tuber diameter (mm)	Tuber yield (kg ha ⁻¹)
	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22	2021/22	2021/22	2021/22
0 kg ha ⁻¹	75.40 ^b	122.40	17.44	21.07	307 ^b	807 ^a	84.32	20.90	588 ^a
75 kg ha ⁻¹	69.50 ^{ab}	116.08	16.31	19.78	381.30 ^c	741 ^a	89.84	22.01	852 ^b
150 kg ha ⁻¹	77.10 ^b	129.34	15.17	22.22	376 ^c	1019 ^b	84.65	20.14	873 ^b
300 kg ha ⁻¹	59.50 ^a	121.95	16.14	20.14	248.30 ^a	692 ^a	94.07	19.31	617 ^a
P-value	0.005	0.531	0.158	0.088	<.001	0.018	0.490	0.121	<.001
± sed	4.89	8.864	0.966	0.994	21.18	103.1	7.228	1.117	71.7
N-top dressing (AN, 34.5% N)									
0 kg ha ⁻¹	66.40	110.56 ^a	15.22 ^a	19.67 ^a	290.50 ^a	632 ^a	86.41 ^{ab}	20.90 ^b	585 ^a
75 kg ha ⁻¹	76.30	125.75 ^{ab}	15.75 ^a	20.70 ^a	348.40 ^b	882 ^b	73.92 ^a	18.05 ^a	502 ^a
150 kg ha ⁻¹	69.80	139.68 ^b	18.63 ^b	22.98 ^b	329.70 ^{ab}	1012 ^b	91.85 ^b	21.66 ^b	990 ^b
300 kg ha ⁻¹	68.90	113.78 ^a	15.47 ^a	19.86 ^a	344 ^b	732 ^{ab}	100.70 ^b	21.75 ^b	853 ^b
P value	0.239	0.011	0.004	0.009	0.042	0.005	0.008	0.007	<.001
± sed	4.89	8.864	0.966	0.994	21.18	103.1	7.228	1.117	71.7
Compound NPK Fertiliser (7:14:7) × N-top dressing (AN, 34.5% N)									

P value	0.589	0.006	0.314	0.035	<.001	<.001	0.035	0.180	<.001
± sed	9.77	17.729	1.933	1.989	42.36	206.3	14.456	2.233	143.4

*Note: Means followed by *same letter* superscripts within the same column are significantly different at $P < 0.05$

There was a significant interaction ($P < 0.05$) between compound NPK and AN fertiliser application rates on tuber length at the Zvimba and Chikombedzi sites in the second growing season (Table 4.2). The combination of 0 kg ha⁻¹ compound NPK + 75 kg ha⁻¹ AN treatment produced longer tubers than the control treatment, similar to other higher fertiliser application rates viz. 150 kg ha⁻¹ compound NPK + 150 kg ha⁻¹ AN and 300 kg ha⁻¹ compound NPK + 150 kg ha⁻¹ AN (Figure 4.1). All the other compound NPK and AN combinations had similar tuber lengths to the control treatment at the Zvimba site (Figure 4.1). At the Chikombedzi site, in the second growing season, there was no significant difference between tuber length recorded in the control treatment (0 kg ha⁻¹ compound NPK + 0 kg ha⁻¹ AN) and all other treatment combinations in which higher fertiliser rates were applied (Figure 4.2).

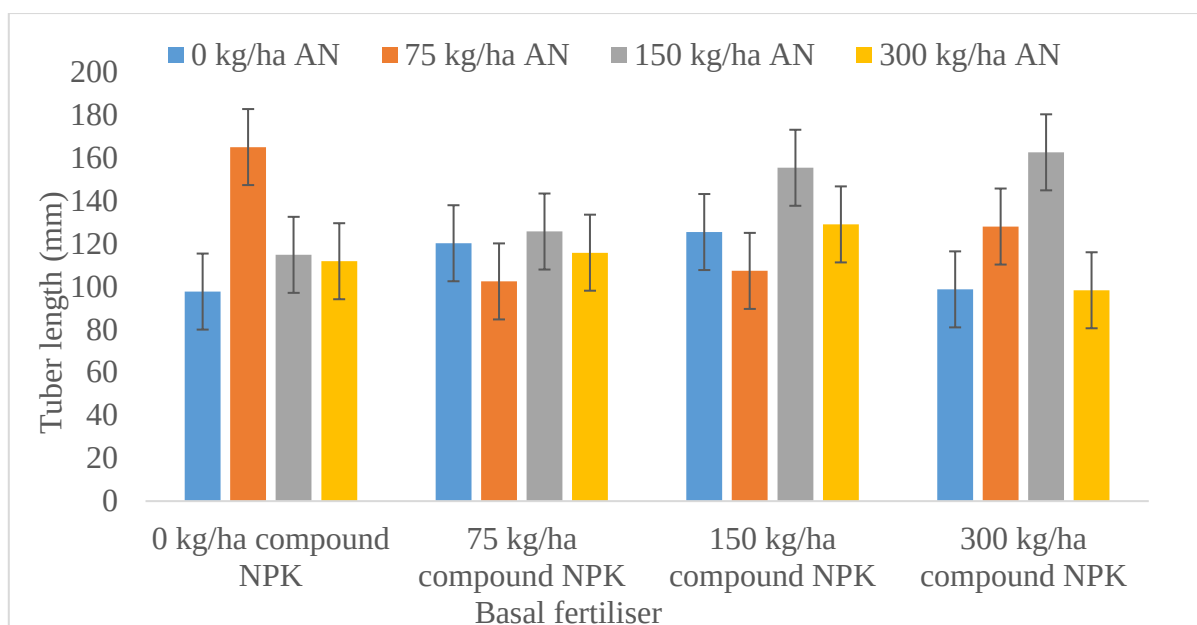


Figure 4.1: Interaction between compound NPK fertiliser and AN fertiliser application rates on tuber length in 2021/22 growing season at Murungweni farm in Zvimba, Zimbabwe. (Error bars are $\pm$ standard error of difference (sed) for the comparison of AN fertiliser application rate means within and across compound NPK fertiliser application rate)

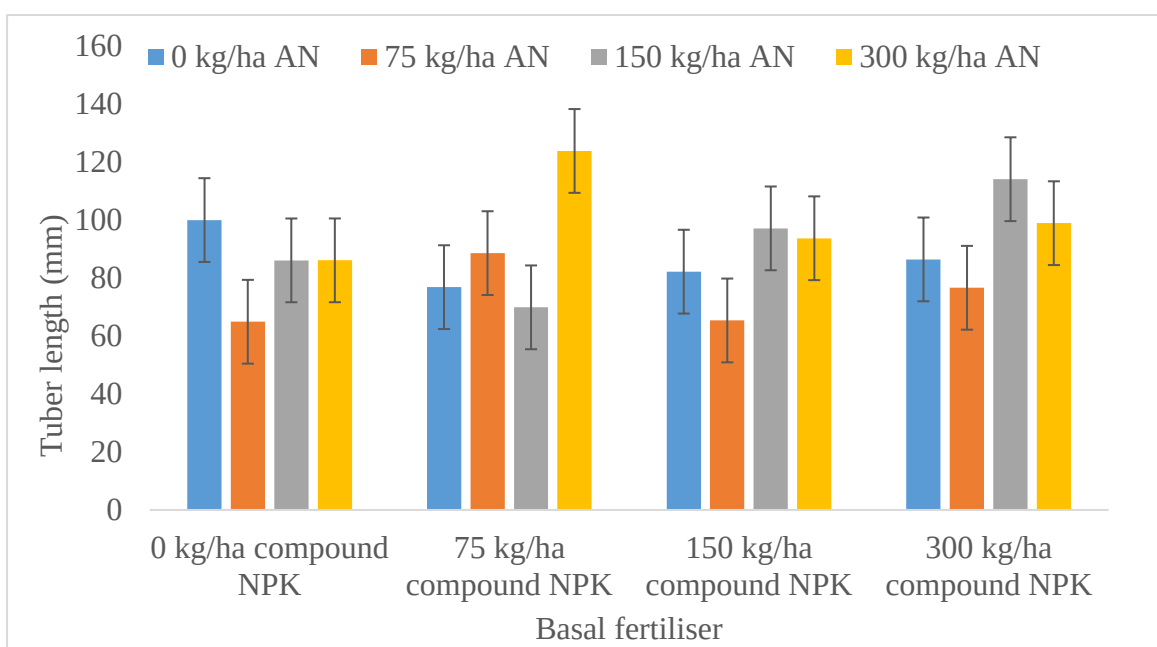


Figure 4.2: Interaction between compound NPK fertiliser and AN fertiliser application rates on tuber length in 2021/22 growing season at the Chikombedzi site in Zimbabwe. (Error bars are $\pm$ standard error of difference (sed) for the comparison of AN fertiliser application rate means within and across compound NPK fertiliser application rate)

4.3.2 *Neorautanenia brachypus* tuber diameter

Effect of individual macronutrients and their combinations on N. brachypus tuber diameter

In both the 2020/21 and 2021/22 growing seasons, fertiliser treatments had a significant effect ($P < 0.05$) on tuber diameter at both sites (Table 4.1). There was no significant difference in tuber diameter between the control treatment and all other fertiliser treatments, except for the 128 kg ha⁻¹ P₂O₅ + 121 kg ha⁻¹ K₂O treatment which reduced tuber diameter by 55% in the 2020/21 season at the Zvimba site (Table 4.1). In the second growing season after planting (2021/2022), in the same plot, the 128 kg ha⁻¹ P₂O₅ + 121 kg ha⁻¹ K₂O treatment reduced tuber diameter by 20% compared to the control treatment (Table 4.1). At the Chikombedzi site, tuber diameter was 19-35% greater than the control treatment when 121 kg ha⁻¹ K₂O, 145 kg ha⁻¹ N + 128 kg ha⁻¹ P₂O₅, 128 kg ha⁻¹ P₂O₅ + 121 kg ha⁻¹ K₂O, and 145 kg ha⁻¹ N + 128 kg ha⁻¹ P₂O₅ + 121 kg ha⁻¹ K₂O and were applied (Table 4.1).

Effect of compound NPK and AN fertiliser application rates on N. brachypus tuber diameter

Compound NPK fertiliser application rates had no significant effect ($P > 0.05$) on tuber diameter of *N. brachypus* at both Zvimba and Chikombedzi sites in the 2020/21 and 2021/22 seasons (Table 4.2). The effects of AN fertiliser treatments were significant ($P < 0.05$) on tuber diameter at the Zvimba site in both the growing seasons and at the Chikombedzi site (Table 4.2). At the Zvimba site, there was no significant difference in tuber diameter between the control treatment and all other AN fertiliser treatments, except for the 150 kg ha⁻¹ AN fertiliser treatment that increased tuber diameter by 22.40% in the 2020/21 growing season, relative to the control treatment (Table 4.2). At the Chikombedzi site, the control treatment recorded a higher tuber diameter than 75 kg ha⁻¹ AN fertiliser, similar to higher fertiliser application rates of 150 kg ha⁻¹ and 300 kg ha⁻¹ AN fertiliser (Table 4.2). There was a significant interaction ($P < 0.05$) between compound NPK fertiliser and AN fertiliser application rates on tuber diameter at the Zvimba site in the 2021/22 season (Table 4.2). Tuber diameter was significantly greater than the control treatment when 0 kg ha⁻¹ compound NPK + 75 kg AN, 0 kg ha⁻¹ compound NPK + 150 kg ha⁻¹ AN, 75 kg ha⁻¹ compound NPK + 150 kg ha⁻¹ AN, 150 kg ha⁻¹ compound NPK + 150 kg ha⁻¹ AN, 150 kg ha⁻¹ compound NPK + 300 kg ha⁻¹ AN and 300 kg ha⁻¹ compound NPK + 75 kg ha⁻¹ AN were applied (Figure 4.3). All other compound NPK and AN application rates combinations had similar tuber diameter with the control treatment at the Zvimba site (Figure 4.3).

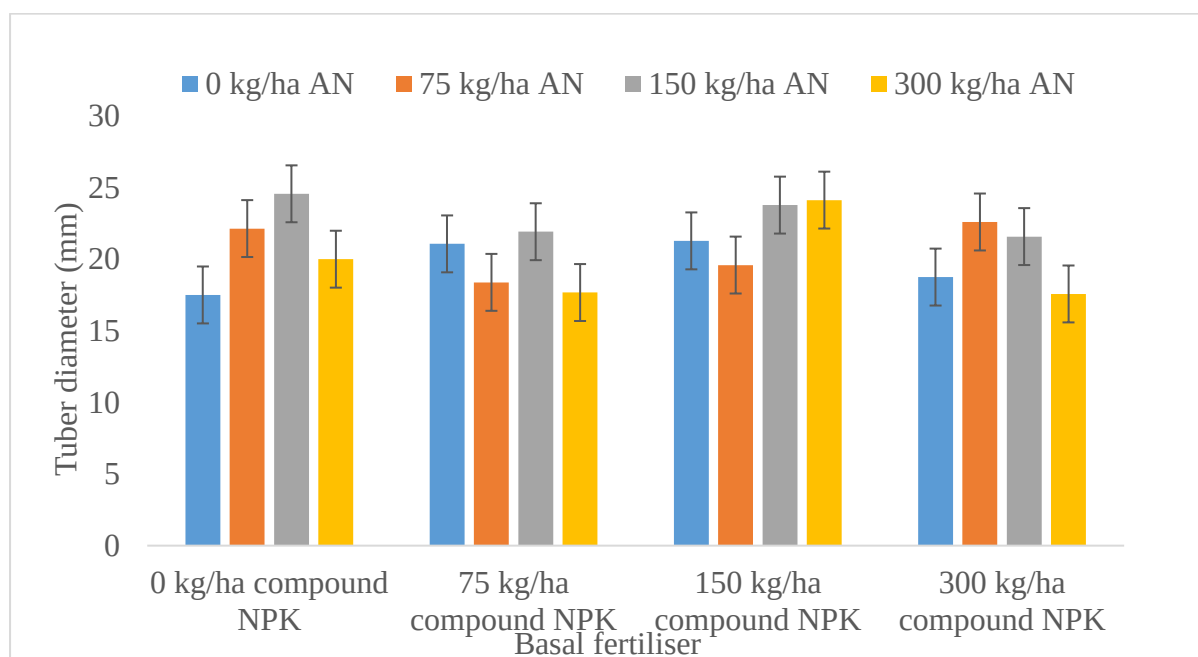


Figure 4.3: Interaction between compound NPK fertiliser and AN fertiliser application rates on tuber diameter in 2021/22 growing season at Murungweni farm in Zvimba, Zimbabwe. (Error bars are $\pm$ standard error of difference (sed) for the comparison of AN fertiliser application rate means within and across compound NPK fertiliser application rate)

4.3.3 *Neorautanenia brachypus* tuber yield

Experiment 1: Effect of individual macronutrients and their combinations on N. brachypus tuber yield

Analysis of variance revealed a significant effect ($P < 0.05$) of the fertiliser treatments on the tuber yield of *N. brachypus* at both the Zvimba and Chikombedzi sites (Table 4.1). There was no significant difference in tuber yield between the control and all fertiliser treatments except for the $145 \text{ kg ha}^{-1} \text{ N}$ and $128 \text{ kg ha}^{-1} \text{ P}_2\text{O}_5 + 121 \text{ kg ha}^{-1} \text{ K}_2\text{O}$ treatments which reduced tuber yield by 79% and by 32%, respectively, in the 2020/21 growing season at the Zvimba site (Table 4.1). In the second season after planting (2021/22), in the same plot, application of $145 \text{ kg ha}^{-1} \text{ N}$ fertiliser significantly reduced tuber yield by 39% relative to the control treatment (Table 4.1). Similarly, at the Chikombedzi site, tuber yield did not significantly differ between the control and all fertiliser treatments except for $145 \text{ kg ha}^{-1} \text{ N}$ and $145 \text{ kg ha}^{-1} \text{ N} + 121 \text{ kg ha}^{-1} \text{ K}_2\text{O}$ fertiliser that significantly reduced tuber yield by 39% and by 18% over the control

treatment in the 2021/22 growing season. Furthermore, at the Chikombedzi site, the 128 kg ha⁻¹ P₂O₅ treatment increased tuber yield by 33% compared to the control treatment (Table 4.1).

Experiment 2: Effect of compound NPK and AN fertiliser application rates on N. brachypus tuber yield

Compound NPK and AN fertiliser treatment significantly affected ($P < 0.05$) tuber yield of *N. brachypus* at both the Zvimba (2020/21 and 2021/22) and Chikombedzi (2021/22) sites during the period of study (Table 4.2). There was a significant interaction ($P < 0.05$) between compound NPK fertiliser application rates and AN application rate on tuber yield at both the Zvimba (2020/21 and 2021/22) and Chikombedzi (2021/22) sites (Table 4.2). At Zvimba (2020/21), tuber yield was significantly higher in the 75 kg ha⁻¹ compound NPK + 0 kg ha⁻¹ AN, 75 kg ha⁻¹ compound NPK + 75 kg ha⁻¹ AN, 75 kg ha⁻¹ compound NPK + 150 kg ha⁻¹ AN, 150 kg ha⁻¹ + 75 kg ha⁻¹ AN, 150 kg ha⁻¹ compound NPK × 150 kg ha⁻¹ AN, and 150 kg ha⁻¹ compound NPK + 300 kg ha⁻¹ AN treatment than in the control treatment where no fertiliser was applied (Figure 4.4a). All other treatment combinations of compound NPK and AN had similar or lower tuber yield than the control (Figure 4.4a). In the second growing season, the highest tuber yield was recorded in the 0 kg ha⁻¹ compound NPK + 75 kg ha⁻¹ AN, the 150 kg ha⁻¹ compound NPK + 150 kg ha⁻¹ AN and the 150 kg ha⁻¹ compound NPK × 300 kg ha⁻¹ AN treatment combination. The control, 0 kg compound NPK × 300 kg AN ha⁻¹ and 75 kg compound NPK × 75 kg AN ha⁻¹ had similar and the lowest tuber yield (Figure 4.4b). Tuber yield was significantly higher in the 150 kg ha⁻¹ compound NPK + 150 kg ha⁻¹ AN treatment followed by the 75 kg ha⁻¹ compound NPK + 300 kg ha⁻¹ AN than in the control treatment (Figure 5). All other treatment combinations of compound NPK and AN had similar tuber yield with the control that received no fertiliser (Figure 4.5).

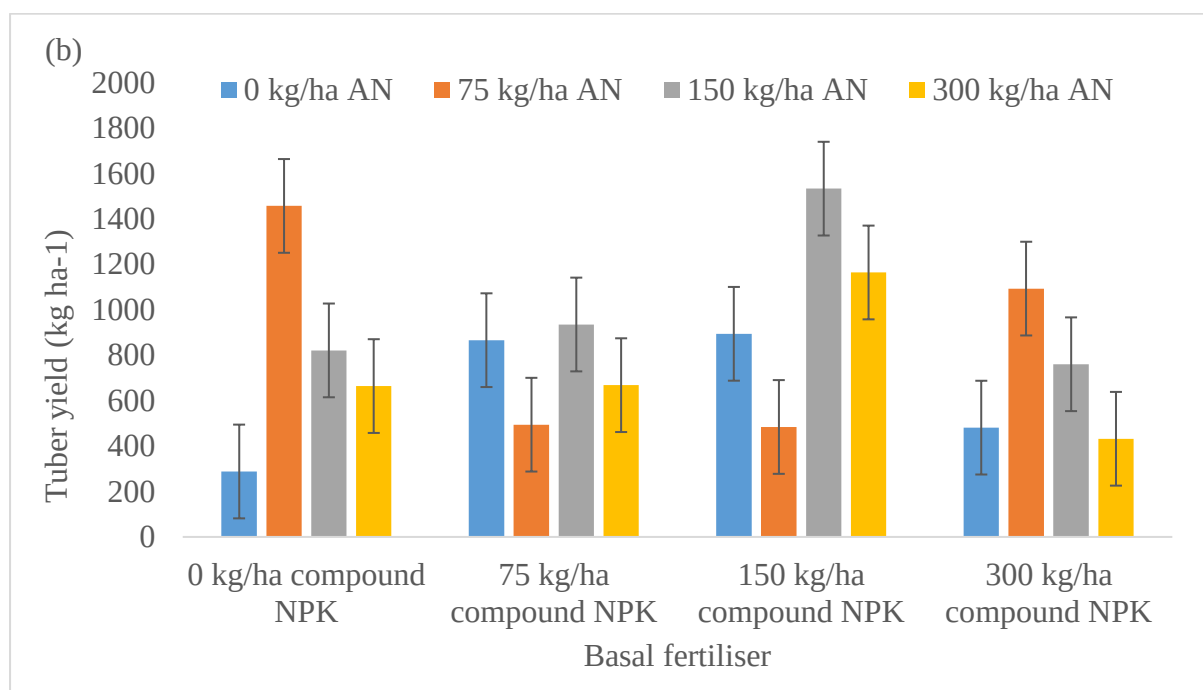
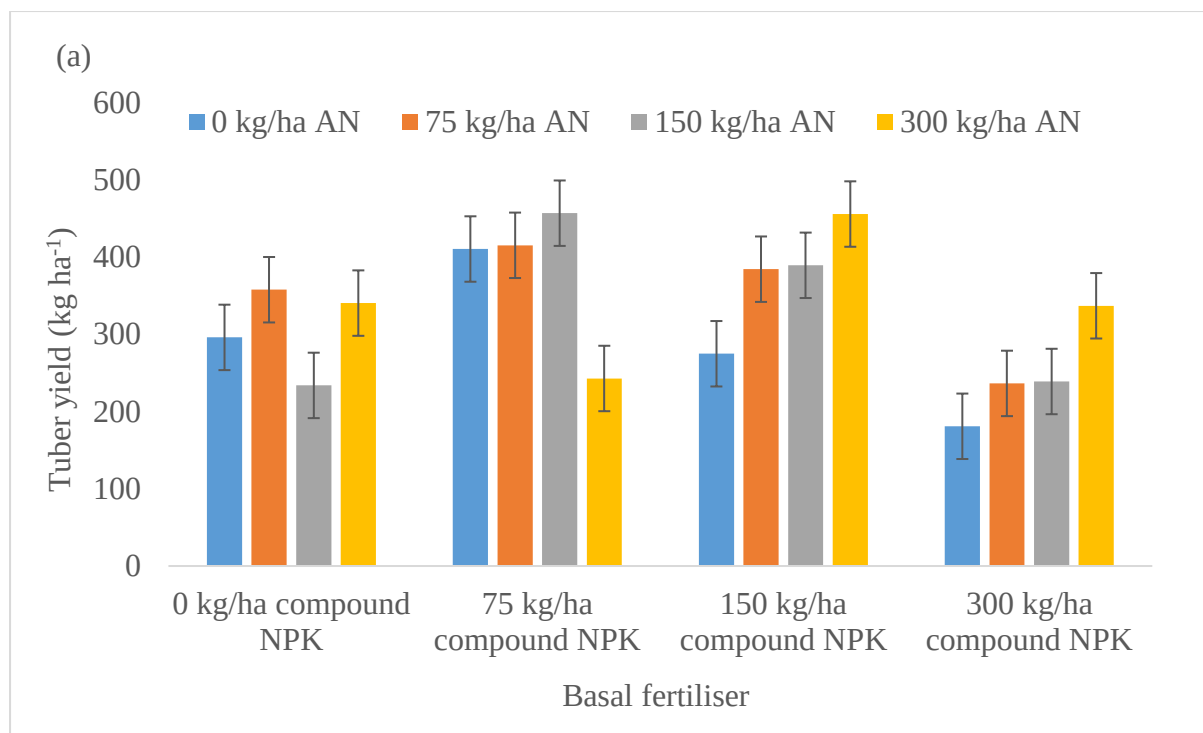


Figure 4.4: Interaction between compound NPK fertiliser and AN fertiliser application rates on tuber yield in (a) 2020/21 (b) 2021/22 growing season at the Zvimba site in Zimbabwe. (Error bars are $\pm$ standard error of difference (sed) for the comparison of AN fertiliser application rate means within and across compound NPK fertiliser application rate)

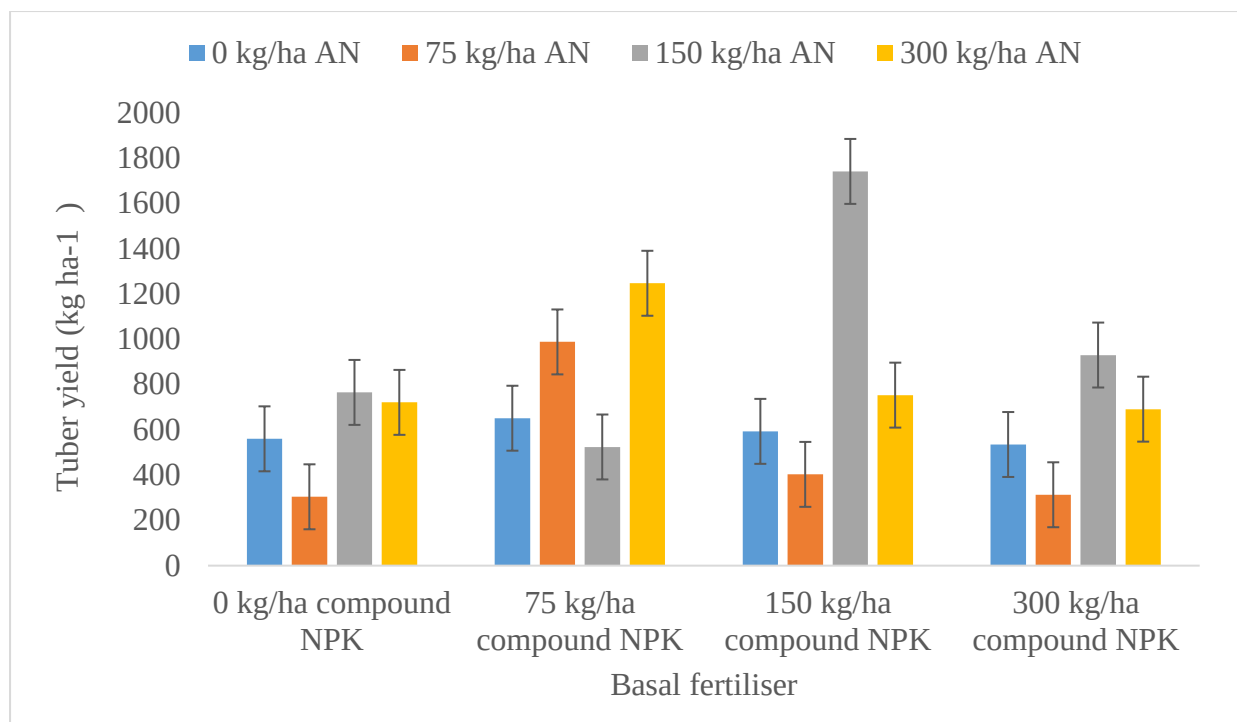


Figure 4.5: Interaction between compound NPK fertiliser and AN fertiliser application rates on tuber yield in the 2021/22 growing season at the Chikombedzi site, Zimbabwe. (Error bars are $\pm$ standard error of difference (sed) for the comparison of AN fertiliser application rate means within and across compound NPK fertiliser application rate)

4.4 Discussion

This study was designed to determine the effects of individual macronutrients (N, P and K) their combination (NP, NK, PK and NPK) and compound NPK $\times$ AN fertiliser application on *N. brachypus* tuber length, diameter and yield. In Experiment 1, applying 145 kg ha⁻¹ N consistently reduced tuber yield in both growing seasons and sites. This reduction may be due to nutrient imbalance caused by excessive nitrogen, which can disrupt the plant's nutrient uptake, limit the availability of other essential nutrients and increase the plant's susceptibility to diseases and physiological disorders (Miyasaka et al., 2002). This also suggests that with the omission of macronutrients P and K, a reduction in tuber yield is high. A similar mineral-nutrient imbalance effect was reported for potato in China by Tan *et al.* (2016), who observed that applying nitrogen alone resulted in a 47% lower tuber yield compared to using a balanced NPK fertiliser package. This reduction in tuber yield can also be attributed to excess accumulation of N in the aboveground parts of *N. brachypus*, which could easily cause vegetative overgrowth and source-sink imbalance (Wu *et al.*, 2016, Duan *et al.*, 2018, Munda

et al., 2019). These results are in harmony with the findings of Hartemink *et al.* (2000), who discovered that the root yield of sweet potato was negatively affected by N fertilisers while application of N increased aboveground biomass. The reduction in tuber yield when N was applied alone may also be attributed to N inhibiting N-fixation in *N. brachypus*, which is an N-fixing legume species (Kaseke, 2019; Li *et al.*, 2016).

A significant increase in tuber yield was only observed at the Chikombedzi site in the 2021/22 growing season in the 128 kg ha⁻¹ P₂O₅ treatment. This shows the importance of P in *N. brachypus* growth under P-deficient soils. The soils at the Chikombedzi site were deficient in P, thus the positive response by *N. brachypus* to the application of 128 kg ha⁻¹ P₂O₅. This agrees with Munyahali *et al.* (2017), who concluded that application of NPK fertilisers in fields with low fertility results in large responses to mineral fertilisers. The increase in *N. brachypus* yield in the 128 kg ha⁻¹ P₂O₅ treatment could be associated with the significant increases in tuber length. This study's results align with previous studies on tropical RTCs, that attributed the significant increase in tuber yield to the function of P in maximising the metabolic processes of plants including stimulation of tuberisation, translocation of assimilates to the growing tubers and regulating production.

The observed lack of significant difference in tuber yield between the control and the 121 kg ha⁻¹ K₂O treatment as well as other straight fertiliser combinations (NP, NK, PK and NPK) at both sites, suggest that *N. brachypus*, similar to most wild RTC plants, does not benefit from NPK fertiliser application. The exception is the increase in tuber yield with the application of P fertiliser at the Chikombedzi site, which aligns with the findings of Pisa *et al.* (2022). Tropical and sub-tropical RTCs' tuber yield has not always increased with the use of inorganic straight fertilisers. These results are similar to those observed for cassava, sweet potato, and potato, where many researchers reported a negative or no response to the application of inorganic fertiliser (Duan *et al.*, 2018, Uwah *et al.*, 2013, Setu and Mitiku, 2020). The researchers attributed the negative and no response to several factors, such as cultivar type (fertiliser-responsive, indifferent and depressive), soil type, and climatic conditions during the experimental period (Wu *et al.*, 2016, Kaupa and Rao, 2014, Duan *et al.*, 2018). Furthermore, the observed negative response to fertiliser treatments in this research could be associated with a significant decrease in tuber growth parameters (tuber length and diameter). Gelaye *et al.* (2022) and Tan *et al.* (2016) attributed the small tuber sizes to soil nutrient imbalances and the negative effects of root-induced changes in soil pH.

As explained by Tan *et al.* (2016), balanced nutrient management is key to improving fertiliser use efficiency. Experiment 2 results confirmed the essential role of applying balanced fertiliser as tuber length, diameter, and yield were all significantly influenced by compound NPK + AN application. In less fertile soils, the tuber yield was consistently higher in the 150 kg ha⁻¹ compound NPK + 150 kg ha⁻¹ AN and the 150 kg ha⁻¹ compound NPK + 300 kg ha⁻¹ AN treatments. While at Chikombedzi site, the highest tuber yield was observed in 150 kg ha⁻¹ compound NPK + 150 kg ha⁻¹ AN and 75 kg ha⁻¹ compound NPK + 300 kg ha⁻¹ AN. The results indicate that *N. brachypus* requires compound NPK and AN fertiliser to increase yield, and this is dependent on soil fertility status. This was similar to observations made in cassava, Jerusalem artichoke, and potato, whereby tuber yield increased with an increase in application rates of NPK (Munyahali *et al.*, 2017, Wierzbowska *et al.*, 2021, Getahun *et al.*, 2020, Grzebisz *et al.*, 2017, Grzebisz *et al.*, 2018). It follows that the development of mineral nutrient management strategies requires the knowledge of the soil type of the area.

Previous studies on sandy, sandy loam and sandy silt soils showed that application of NPK fertiliser significantly increased tuber yield and was directly correlated with an increase in morphological traits and yield components of cassava (Mwamba *et al.*, 2021), and potato (Kołodziejczyk, 2014, Tan *et al.*, 2016, Sandhu *et al.*, 2013). In this study, in poor sandy soils, tuber diameter and tuber length were consistently increased in the 0 kg ha⁻¹ compound NPK + 75 kg ha⁻¹ AN and the 150 kg ha⁻¹ compound NPK + 150 kg ha⁻¹ AN. These results suggest that the response of tuber yield was a true image of the response of tuber diameter and tuber length: high tuber yield was consistently associated with high tuber diameter and length. Notably, the results of this study showed that the application of compound NPK and AN had been shown to promote *N. brachypus* tuber growth and yield, as reported in previous RTC studies. This might be attributed to increased branching and leaf production, efficiency of photosynthesis, production and translocation of photoassimilates caused by macronutrients in these fertilisers (Munyahali *et al.*, 2017, Luz *et al.*, 2013, Sandhu *et al.*, 2013).

In contrast to the tuber yield response to NPK fertiliser in sandy soils, most research showed that the tuber yield of RTCs in clayey and clay loam soils showed a quadratic response to an increase in NPK fertiliser. The highest tuber yield is obtained at a species-specific optimum fertiliser application rate and any further increase above the optimum will result in yield depression (Santos *et al.*, 2018, Noor *et al.*, 2015, Gelaye *et al.*, 2022). Gelaye *et al.* (2022) and Oliveira *et al.* (2020) have attributed the yield depression to net diminishing returns, increased

vegetative growth at the expense of tuber growth, and mineral nutrient imbalance depending on the NPK composition. This conforms with the high tuber diameter, length, and yield recorded in the 0 kg/ha compound NPK $\times$ 75 kg/ha AN, 150 kg/ha compound NPK $\times$ 150 kg/ha AN, and 75 kg/ha compound NPK $\times$ 300 kg/ha AN treatments, and the lower yield recorded with high NPK rates.

4.5 Conclusion

This study observed the effects of individual mineral nutrients N, P, and K and their additive effects on tuber growth and yield during the early growth stages of *N. brachypus*. The findings of the first experiment showed that application of 145 kg ha⁻¹ N, 128 kg ha⁻¹ P₂O₅ + 121 kg ha⁻¹ K₂O, and 145 kg ha⁻¹ N + 121 kg ha⁻¹ K₂O can reduce *N. brachypus* tuber yield and yield parameters compared to no fertiliser application. Furthermore, the results suggest that in less fertile soils, the application of individual macronutrients as straight fertilisers cannot maximise tuber yield, while in more fertile soils, the application of P fertiliser is recommended for increasing tuber length and yield. This shows that *N. brachypus* can be domesticated successfully with the use of phosphorus-straight fertilisers. However, the interactions of compound NPK plus AN top dressing did not show a clear trend of how *N. brachypus* yield was responding to different fertiliser application rates with most of the treatment combinations, except the ones that attained the highest yield, producing tuber length, diameter and yield similar to the no fertiliser control. Therefore, more research is needed to understand the fertiliser requirements of *N. brachypus*, which like other wild RTCs, showed that it may require little or no fertiliser. From a domestication perspective, for smallholder farmers in the Zvimba site or under similar environmental conditions, the application of 75 kg ha⁻¹ AN only is recommended, for it gives higher tuber yields than no fertiliser application, similar to the application of 150 kg ha⁻¹ compound NPK + 150 kg ha⁻¹ AN.

CHAPTER 5: SYNTHESIS

5.1 General Discussion

5.1.1 Introduction

In this dissertation, an exploratory study was done on the specific agronomic recommendations on plant spatial arrangements, population density, and fertiliser requirements for root and tuber plants (RTCs). The dissertation's first chapters put the different findings on the effects of fertiliser application and spatial arrangement on RTCs into perspective concerning how they can be integrated into the domestication of *Neorautanenia brachypus* (Harms) C.A. Sm. An indigenous wild leguminous plant that has recently been adopted as a drought survival feed in the south-eastern lowveld of Zimbabwe. This tuber has enough nutrients to maintain ruminant livestock during droughts. Apart from its nutritional value as a feed, *N. brachypus* has demonstrated anthelmintic properties when given to ruminant animals. This study investigated plant spatial arrangements and population densities to identify the optimal for maximising the productivity of *N. brachypus* on two different soil types: arenosols and eutric vertisols. In addition, the effect of individual macronutrients N, P, and K, their combinations, and the fertiliser application rates of compound NPK and AN on *N. brachypus* tuber yield were analysed to determine their impact on improving *N. brachypus* productivity and their potential to increase tuber yield and yield components. These agronomic analyses will feed into the conservation and domestication efforts on *N. brachypus* in Zimbabwe.

5.1.2 *The effect of plant spacing and fertiliser application on the conservation and domestication of N. brachypus*

For the domestication of wild plants and the increasing productivity of new hybrids, understanding the agronomic requirements of a crop is essential. This involves the evaluation of propagation methods, assessing soil requirements, water requirements, climate suitability, plant spacing, plant population density and nutrient management requirements. This is crucial for maximising resource utilisation and for efficient plant growth and yield. The evaluation of these agronomic traits is essential in developing irrigation strategies, nutrient-soil amendments, pests and diseases management strategies, and can extend to developing harvesting and post-harvest handling techniques. In this study, the agronomic requirements assessed for domestication of *N. brachypus* were the effects of plant spatial arrangements, population densities and fertiliser application on the yield and tuber size of *N. brachypus*. Determining the

ideal plant spatial arrangements and population densities maximises resource utilisation and supports efficient tuber growth and yield. In addition, managing nutrient requirements through balanced fertiliser application enhances nutrient uptake and crop development. From the observations reported in the preceding chapters of this dissertation, it can be concluded that:

- The interaction between inter-row and in-row has an effect on *N. brachypus*’ tuber length, diameter, and yield in less fertile arenosol soils. The spacing of 0.60 m inter-row $\times$ 0.30 m in-row with a plant population density of 55555 plants per hectare maximises *N. brachypus* tuber growth and yield productivity.
- In more fertile eutric vertisol soils, there is no interaction between inter-row and in-row spacing on *N. brachypus*’ tuber yield, though the narrow inter-row spacing of 0.45 m resulted in the highest yield, averaged across in-row spacing.
- In more fertile soils, application of 128 kg ha P_2O_5 is recommended for maximising *N. brachypus* tuber length and tuber yield. However, in both arenosols and eutric vertisols application of 145 kg ha⁻¹ N, 128 kg ha⁻¹ P_2O_5 + 121 kg ha⁻¹ K_2O and 145 kg ha⁻¹ N + 121 kg ha⁻¹ K_2O reduces *N. brachypus* tuber yield and yield parameters compared to no fertiliser application.
- In low fertility soils, application of 0 kg ha⁻¹ compound NPK + 75 kg ha⁻¹ AN is recommended, for it increases tuber yields more than no fertiliser application and has similar effects with higher application rates (150 kg ha⁻¹ compound NPK + 150 kg ha⁻¹ AN and 150 kg ha⁻¹ compound NPK + 300 kg ha⁻¹ AN). Whereas, in high fertile soils with low annual rainfall, application of 150 kg ha⁻¹ compound NPK + 150 kg ha⁻¹ AN and 75 kg ha⁻¹ compound NPK + 300 kg ha⁻¹ AN increases tuber size and yield of *N. brachypus*.

5.1.3 Plant spatial arrangement, population density, and fertiliser application on tuber yield of *N. brachypus*

Among the agronomic practices that influence tuber growth and yield, plant spatial arrangement and population density are key to achieving high yields (Law-Ogbomo & Osaigbovo, 2014; Liu, Liu, Zhang, & He, 2014). Plant spatial arrangements and population density have a significant influence on the growth and development of *N. brachypus*. They influence the extent of intra-specific competition between plants in a cropping system for growth resources (Zaimoglu Onat *et al.*, 2017). At wide plant spatial arrangements and low population density competition for growth resources is minimal. This was observed in *N.*

brachypus at a spacing of 0.6 m inter-row $\times$ 0.45 m in-row with a plant population of 37 037 plants per hectare. The high tuber length of *N. brachypus* observed maybe as a result of low competition for nutrients, soil moisture and light. This is in line with reports by Demisie and Tolessa (2018) who reported that at wider plant spacing, bulb length is increased, but at narrow plant spacing, tuber length is reduced. This was also true at 0.75 m inter-row $\times$ 0.45 m in-row. Less competition for growth resources results in increased plant vigour and tuber development. In contrast, the tuber diameter of *N. brachypus* decreased with an increase in plant population and a reduction in spatial arrangement. Tuber diameter was highest at a plant population of 55555 with a plant spacing of 0.60 m $\times$ 0.30 m. Narrow plant spacing results in rapid canopy cover which suppresses the growth of weeds and reduces intraspecific plant competition for growth resources (Wees *et al.*, 2016). This therefore ensures adequate nutrient and moisture availability for *N. brachypus* tuber initiation and development. A rapid canopy cover at closer plant spacing also ensures full ground cover reducing the amount of light reaching the ground and soil water evaporation (Meena *et al.*, 2020). This maintains a high content of soil available water and increases infiltration, thus increasing plant growth and tuber yield. In this research, at the Zvimba site, tuber yield was highest at a plant population of 55555 plants per hectare at a plant spacing of 0.60 m $\times$ 0.30 m. This might have also been attributed to high plant densities that increase the number of *N. brachypus* tubers being harvested per unit area of land. This is in line with the findings of Zaimoglu Onat *et al.* (2017) who observed that plant yield increases with an increase in plant population. However, at high population densities there is increased intra-specific competition for growth resources. Therefore, there is a need for mineral nutrient replenishment to maximise yield.

At high plant densities, soil fertility management is key in increasing tuber yield. *N. brachypus* grows well in different soil types (Murungweni *et al.*, 2012). However, to enhance its tuber yield, there is a need to increase the amount of soil nutrients available for plant uptake. *N. brachypus* requires P at the early stages of plant growth for root and shoot development (Chapter 4). This hastens plant growth and ensures early onset of tuber initiation (Zewide *et al.*, 2012). For vegetative growth and canopy production, root and tuber plants require N (Munda *et al.*, 2019). Nitrogen is an essential constituent of chlorophyll and proteins; thus, its application enhances photosynthetic, meristematic, and more intense physiological activities in the plant which favoured the synthesis of more assimilates (Noor *et al.*, 2015; Uwah *et al.*, 2013). Potassium is one of the key nutrients which is required for enzymatic activities, hence contributing to the well-development of photosynthetic surfaces and the production and

translocation of assimilates to the root for starch synthesis (Howeler, 2001). This is in line with the findings from this research, in arenosols the combination of N, P, and K supports tuber growth. This shows that balanced mineral nutrients are essential for tuber development. The omission of P and K reduced tuber length by 16% in comparison to the control plots. This is because of a deficiency of P, an essential nutrient that is required for all energy reactions and K, a key component in the synthesis of starch in the storage roots. This conforms to the findings of Tan *et al.* (2016) who observed that application of N alone does not enhance tuber development and concluded that a balanced mineral nutrient supply increases tuber size. This was also confirmed by the decrease in tuber diameter after the application of PK and NK (Chapter 4). The nutrient imbalance may affect starch synthesis and might result in the accumulation of soluble carbohydrates thus the development of poor-quality and small-sized tubers (Turamyenyirijuru, 2013). Application of N alone might affect nutrient use efficiency. Graciano, Goya, Frangi, and Guamet (2006) stated that plants might not respond to the application of N when P is deficient.

It is therefore of paramount importance that the application of macronutrients be balanced. In most Zimbabwean communities, smallholder farmers use compound NPK to apply balanced N, P, and K nutrients. The type of compound fertiliser and fertiliser application rates depend on the soil nutrient status prior to production. At the Zvimba site with infertile sandy soils deficient in all the macronutrients, the findings of this research showed that tuber length was highest in plots that received 0 kg ha⁻¹ NPK fertiliser + 75 kg ha⁻¹ AN application rate. However, at the Chikomedzi site with clay soils deficient in P the tuber length observed in the control treatment was similar to 75 kg ha⁻¹ NPK fertiliser + 300 kg ha⁻¹ AN application rate. Thus, when soil is deficient in macronutrients plants respond to the application of fertiliser because of increased available nutrients for plant uptake. N-top dressing is essential in infertile soils to increase the photosynthetic rate during critical stages of growth such as tuber initiation. Nitrogen availability also increases LAI and enhances radiation interception. This results in increased production of photo-assimilates and thus high plant vigour and tuber development. At both sites, in the second growing season, high *N. brachypus* tuber yield was observed at 150 kg ha⁻¹ NPK fertiliser and at 150 kg ha⁻¹ AN application rate. The research indicated that the application of 300 kg ha⁻¹ compound NPK fertiliser had a negative effect on the tuber yield. The findings showed that plant productivity has a limit and cannot increase indefinitely with increase in fertiliser application rates, following the principle of diminishing returns. The knowledge of plant population density, spatial arrangement, RTCs requirements of inorganic

fertiliser and ideal application rates of N, P, and K for high tuber size and yield are vital for bringing *N. brachypus* to cultivation. The research findings are key to the domestication of *N. brachypus* as a commercial crop, improving its productivity, yield quantity, and reducing the overexploitation of the natural genetic base of *N. brachypus*

5.1.4 *N. brachypus* potential for smallholder farmer adoption

The study's findings on minimal fertiliser needs at dense plant population have direct implications for smallholder farmers, who can adopt *N. brachypus* as a low-input, high-yield crop. The study highlights key findings that align with global and national development goals, specifically SDG 1 (No Poverty) and SDG 2 (Zero Hunger). Notably, the significant increase in tuber length and yield with the application of P, suggest that phosphorus-straight fertilizers are essential for domestication efforts. This improvement in yields supports SDG 2 by enhancing food security and aligns with NDS 1, which aims to boost agricultural productivity and national food self-sufficiency.

Additionally, the study indicates that *N. brachypus* may require minimal fertilization, as treatments like 0 kg/ha compound NPK and 75 kg/ha ammonium nitrate produced similar yields to more fertilizer-intensive treatments. This finding is particularly relevant to smallholder farmers, offering a low-input, high-yield crop option. Reducing input costs while maintaining yields contributes to SDG 1 by improving smallholder profitability and economic resilience, supporting NDS 2's goal of promoting sustainable agricultural practices.

5.2 Conclusion

This study has determined key agronomic requirements for *N. brachypus*, providing critical insights for its domestication and commercial adoption. These findings demonstrated that plant spatial arrangement and population density significantly affect the tuber yield of *N. brachypus* in the two contrasting environments. In arenosols, an interaction of 0.60 m inter-row and 0.3 m in-row spatial arrangement with a plant population of 55 555 plants ha⁻¹ is recommended for the production of *N. brachypus*. In eutric vertisols, a narrow row spacing of 0.45 m is recommended for maximising *N. brachypus* tuber size and yield. The study also indicated that the application of P fertilisers is essential in increasing tuber growth and tuber yield of *N. brachypus* in less fertile arenosol and that the application of N as a straight fertiliser reduces tuber size and yield. The interactions between basal NPK application and AN top dressing

fertiliser did not demonstrate a consistent trend in influencing the yield of *N. brachypus*. Most treatment combinations resulted in tuber length, diameter, and yield comparable to the control group with no fertiliser, except for those that achieved the highest yields. Consequently, further research is necessary to better understand the fertiliser requirements of *N. brachypus*. Like other wild root and tuber crops (RTCs), it appears that *N. brachypus* may need minimal or no fertiliser for optimal growth. These findings underscore the importance of site-specific agronomic practices. The findings also feed into the knowledge system of crop management and agronomy, plant nutrition, and plant conservation. It also showed that domestication and cultivation of the wild *N. brachypus* are feasible under different environmental conditions.

5.3 Implications for further research

The research focused on the agronomic requirements of *N. brachypus* for enhanced productivity and tuber yield in the first two years after planting. From a domestication perspective, it is important to determine the best tuber production strategy regarding the initial spatial arrangement and plant population that will give the highest tuber yield if the production plan is to harvest the tubers after one, two, three or more seasons after planting. *N. brachypus* is a perennial tuber, and its consumable resource requirements will increase as plant and tuber size increase year after year. In addition, replication of this experiment on multi-sites in the dry regions of Zimbabwe is recommended to further verify the results in areas that are suitable for extensive livestock production. An investigation on different timings of fertiliser application can be of importance. Determining the most accurate time for application of fertiliser is key to ensure adequate nutrient supply at critical stages of growth and when nutrient demand is high so as to maximise the utilisation of resources and tuber yield of *N. brachypus*. Therefore, investigating a range of fertiliser application timings will give the most accurate time for fertiliser application. Precise placement of fertiliser increases early growth and promotes less weed emergence, growth and fecundity; therefore, assessment of different fertiliser placement methods in *N. brachypus* production can also maximise tuber yield. Future research should also incorporate organic nutrient sources to replicate its wild environment and investigate the effects of N sources on its nitrogen-fixing capability. This is essential to determine the fertiliser and manure requirements, if any, that align with each tuber production strategy. The other next step for this project is also to analyse the chemical and nutritional composition of the tubers under different fertiliser treatments to determine if fertiliser application has any effect on the anthelmintic properties and the known nutritional composition of the tuber.

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Appendices

Appendix 1: Supplementary data

Supplementary data 1: Risk of bias judgements for each study.

Study	Randomisati on process	Deviation from intended interventi on	Missing outcom e data	Measureme nt of the outcome	Selection of the reported result	Overall
Aboyegi <i>et al.</i> 2019	Low	Low	Some concern s	Low	Some concerns	Some concern
Baimey <i>et al.</i> 2006	Low	Some concerns	Some concern s	High	Low	High
Duan <i>et al.</i> 2018	Low	Low	Low	Low	Low	Low
Duan <i>et al.</i> 2019	Low	Low	Some concern s	Low	Low	Some concern
Gelaye <i>et al.</i> 2022	Low	Low	Low	Low	No informati on	Low
Getahun <i>et al.</i> 2019	Low	Low	Some concern s	Low	Low	Some concern s
Gonçalves <i>et al.</i> 2021	Low	Some concerns	Some concern s	Low	Low	Some concern s
Grzebisz <i>et al.</i> 2018	Low	Some concerns	Low	Low	Low	Some concern s
Grzebisz <i>et al.</i> 2020	Low	Low	High	Low	Low	High
Haile and Boke, 2011	Low	Some concerns	High	Low	Low	High
Katuromunda <i>et al.</i> 2021	Low	No informatio n	Low	Low	Low	Low
Khan <i>et al.</i> 2010	Low	Low	High	Low	Some concerns	High
Khan <i>et al.</i> 2012	Low	Some concerns	High	Low	Some concerns	High
Kołodziejczyk, 2014	Some concerns	Low	Low	Low	Some concerns	Some concern s
Luz <i>et al.</i> 2013	Low	No informatio n	Some concern s	Low	Low	Some concern s

Manorama <i>et al.</i> 2017	Low	Low	Some concerns	Low	Some concerns	Some concerns
Mota <i>et al.</i> 2020	Low	Low	Low	Low	Low	Low
Mozumder <i>et al.</i> 2014	Low	Low	Some concerns	Low	Low	Some concerns
Munda <i>et al.</i> 2019	Low	No information	Some concerns	Low	Low	Some concerns
Munyahali <i>et al.</i> 2017	Low	Low	Low	Some concerns	Low	Some concerns
Mwamba <i>et al.</i> 2021	Low	No information	Some concerns	Low	Low	Some concerns
Noor <i>et al.</i> 2015	Low	Low	Low	Low	Low	Low
Nurmanov <i>et al.</i> 2019	High	Low	High	Some concerns	Some concerns	High
Sandhu <i>et al.</i> 2013	High	Low	High	Some concerns	Some concerns	High
Santos <i>et al.</i> 2018	High	Low	Low	Low	Some concerns	High
Setu and Mitiku, 2019	Low	Low	Low	Low	Low	Low
Sinta and Garo, 2021	Low	Some concerns	Low	Low	Low	Some concerns
Suminarti <i>et al.</i> , 2022	High	Low	High	Low	Some concerns	High
Tan <i>et al.</i> 2016	Low	Some concerns	High	Low	Some concerns	High
Uwah <i>et al.</i> 2013	Low	Low	Low	Low	Low	Low
Wang <i>et al.</i> 2014	Low	Low	Low	Low	Low	Low
Wierzbowska <i>et al.</i> 2021	Low	Low	Some concerns	Low	Some concerns	Some concerns
Yadav <i>et al.</i> 2022	Low	Low	Some concerns	Some concerns	Low	Some concerns
Yagi <i>et al.</i> 2019	Low	Low	High	Some concerns	No information	High
Yakimenko and	Low	Some concerns	High	Some concerns	Low	High

Naumova, *et al.* 2021

Zebbarth *et al.* 2011

Low

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Appendix 2: Analysis of variance for the effect of inter-row and in-row spacing on tuber length at the Zvimba site in the 2020/21 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	671.94	335.97	8.51	
Rep.*Units* stratum					
Inter_row_spacing	2	723.70	361.85	9.17	0.005
In_row_spacing	1	1.23	1.23	0.03	0.863
Inter_row_spacing.In_row_spacing					
	2	434.84	217.42	5.51	0.024
Residual	10	394.62	39.46		
Total	17	2226.34			

Appendix 3: Analysis of variance for the effect of inter-row and in-row spacing on tuber diameter at the Zvimba site in the 2020/21 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	17.656	8.828	6.57	
Rep.*Units* stratum					
Inter_row_spacing	2	123.307	61.653	45.90	<.001
In_row_spacing	1	1.989	1.989	1.48	0.252
Inter_row_spacing.In_row_spacing					
	2	0.399	0.200	0.15	0.864
Residual	10	13.433	1.343		
Total	17	156.784			

Appendix 4: Analysis of variance for the effect of inter-row and in-row spacing on tuber yield at the Zvimba site in the 2020/21 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
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Rep stratum	2	223372.	111686.	51.18	
Rep.*Units* stratum					
Inter_row_spacing	2	144216.	72108.	33.04	<.001
In_row_spacing	1	29922.	29922.	13.71	0.004
Inter_row_spacing.In_row_spacing					
	2	9626.	4813.	2.21	0.161
Residual	10	21821.	2182.		
Total	17	428957.			

Appendix 5: Analysis of variance for the effect of inter-row and in-row spacing on tuber length at the Zvimba site in the 2021/22 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	514.0	257.0	1.21	
Rep.*Units* stratum					
Inter_row_spacing	2	3338.4	1669.2	7.89	0.009
In_row_spacing	1	9.1	9.1	0.04	0.840
Inter_row_spacing.In_row_spacing					
	2	2847.4	1423.7	6.73	0.014
Residual	10	2116.1	211.6		
Total	17	8824.9			

Appendix 6: Analysis of variance for the effect of inter-row and in-row spacing on tuber diameter at the Zvimba site in the 2021/22 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	96.1185	48.0592	156.95	
Rep.*Units* stratum					
Inter_row_spacing	2	14.7677	7.3839	24.11	<.001
In_row_spacing	1	6.1874	6.1874	20.21	0.001
Inter_row_spacing.In_row_spacing					
	2	11.1304	5.5652	18.17	<.001
Residual	10	3.0620	0.3062		
Total	17	131.2660			

Appendix 7: Analysis of variance for the effect of inter-row and in-row spacing on tuber yield at the Zvimba site in the 2021/22 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	133720.	66860.	2.99	
Rep.*Units* stratum					
Inter_row_spacing	2	1802570.	901285.	40.36	<.001
In_row_spacing	1	1168610.	1168610.	52.34	<.001
Inter_row_spacing.In_row_spacing	2	573594.	286797.	12.84	0.002
Residual	10	223293.	22329.		
Total	17	3901788.			

Appendix 8: Analysis of variance for the effect of inter-row and in-row spacing on tuber length at the Chikomedzi site in the 2021/22 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	3373.4	1686.7	10.62	
Rep.*Units* stratum					
Inter-row spacing	2	2942.3	1471.1	9.26	0.005
In-row spacing	1	800.2	800.2	5.04	0.049
Inter-row spacing.In-row spacing	2	1399.7	699.8	4.40	0.042
Residual	10	1589.0	158.9		
Total	17	10104.5			

Appendix 9: Analysis of variance for the effect of inter-row and in-row spacing on tuber diameter at the Chikomedzi site in the 2021/22 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	41.873	20.937	3.81	
Rep.*Units* stratum					
Inter_row_spacing	2	90.190	45.095	8.22	0.008
In_row_spacing	1	33.302	33.302	6.07	0.033

Inter_row_spacing.In_row_spacing	2	5.641	2.821	0.51	0.613
Residual	10	54.883	5.488		
Total	17	225.890			

Appendix 10: Analysis of variance for the effect of inter-row and in-row spacing on tuber yield at the Chikombedzi site in the 2021/22 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	3230696.	1615348.	28.97	
Rep.*Units* stratum					
Inter_row_spacing	2	7408868.	3704434.	66.43	<.001
In_row_spacing	1	634.	634.	0.01	0.917
Inter_row_spacing.In_row_spacing	2	226791.	113395.	2.03	0.182
Residual	10	557678.	55768.		
Total	17	11424666.			

Appendix 11: ANOVA table for the effect of Individual macronutrients, and their combination on tuber length at the Zvimba site in the 2020/21 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	290.5	145.2	0.78	
Block.*Units* stratum					
Fertiliser_combinations	7	5521.0	788.7	4.24	0.010
Residual	14	2603.4	186.0		
Total	23	8414.9			

Appendix 12: ANOVA table for the effect of Individual macronutrients and their combination on tuber diameter at the Zvimba site in the 2020/21 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	100.462	50.231	19.14	
Block.*Units* stratum					
Fertiliser_combinations	7	127.136	18.162	6.92	0.001

Residual	14	36.744	2.625
Total	23	264.342	

Appendix 13: ANOVA table for the effect of Individual macronutrients and their combination on tuber yield at the Zvimba site in the 2020/21 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	116526.	58263.	25.37	
Block.*Units* stratum					
Fertiliser_combinations	7	205802.	29400.	12.80	<.001
Residual	14	32149.	2296.		
Total	23	354477.			

Appendix 14: ANOVA table for the effect of Individual macronutrients and their combination on tuber length at the Zvimba site in the 2021/22 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	438.7	219.4	1.81	
Blocks.*Units* stratum					
Fertiliser_combinations	7	4158.1	594.0	4.90	0.006
Residual	14	1696.0	121.1		
Total	23	6292.9			

Appendix 15: ANOVA table for the effect of Individual macronutrients and their combination on tuber diameter at the Zvimba site in the 2021/22 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	54.274	27.137	13.85	
Blocks.*Units* stratum					
Fertiliser_combinations	7	72.191	10.313	5.26	0.004
Residual	14	27.424	1.959		
Total	23	153.889			

Appendix 16: ANOVA table for the effect of Individual macronutrients and their combination on tuber yield at the Zvimba site in the 2021/22 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	213230.	106615.	4.24	
Blocks.*Units* stratum					
Fertiliser_combinations	7	529618.	75660.	3.01	0.038
Residual	14	351765.	25126.		
Total	23	1094613.			

Appendix 17: ANOVA table for the effect of Individual macronutrients and their combination on tuber length at the Chikombedzi site in the 2021/22 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	275.75	137.87	1.53	
Rep.*Units* stratum					
Fertiliser_combinations	7	3226.47	460.92	5.10	0.005
Residual	14	1265.27	90.38		
Total	23	4767.49			

Appendix 18: ANOVA table for the effect of Individual macronutrients and their combination on tuber diameter at the Chikombedzi site in the 2021/22 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	124.038	62.019	15.78	
Rep.*Units* stratum					
Fertiliser_combinations	7	103.249	14.750	3.75	0.017
Residual	14	55.012	3.929		
Total	23	282.298			

Appendix 19: ANOVA table for the effect of Individual macronutrients and their combination on tuber yield at the Chikombedzi site in the 2021/22 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	102266.	51133.	17.59	

Block.*Units* stratum					
Fertiliser_combinations	7	310445.	44349.	15.25	<.001
Residual	14	40703.	2907.		
Total	23	453415.			

Appendix 20: ANOVA table for the effect of Basal fertiliser and Top dressing on tuber length at the Zvimba site in the 2020/21 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	139.3	69.6	0.49	
Block.*Units* stratum					
Basal_Fertiliser	3	2250.5	750.2	5.23	0.005
Top_dressing	3	638.5	212.8	1.49	0.239
Basal_Fertiliser.Top_dressing					
	9	1079.4	119.9	0.84	0.589
Residual	30	4299.7	143.3		
Total	47	8407.4			

Appendix 21: ANOVA table for the effect of Basal fertiliser and Top dressing on tuber diameter at the Zvimba site in the 2020/21 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	21.339	10.670	1.90	
Block.*Units* stratum					
Basal_Fertiliser	3	31.217	10.406	1.86	0.158
Top_dressing	3	91.132	30.377	5.42	0.004
Basal_Fertiliser.Top_dressing					
	9	62.036	6.893	1.23	0.314
Residual	30	168.098	5.603		
Total	47	373.822			

Appendix 22: ANOVA table for the effect of Basal fertiliser and Top dressing on tuber yield at the Zvimba site in the 2020/21 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	11945.	5972.	2.22	
Block.*Units* stratum					
Basal_Fertiliser	3	143325.	47775.	17.75	<.001
Top_dressing	3	24936.	8312.	3.09	0.042
Basal_Fertiliser.Top_dressing					
	9	171505.	19056.	7.08	<.001
Residual	30	80732.	2691.		
Total	47	432443.			

Appendix 23: ANOVA table for the effect of Basal fertiliser and Top dressing on tuber length at the Zvimba site in the 2021/22 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	1985.1	992.6	2.11	
Blocks.*Units* stratum					
Basal_Fertiliser	3	1059.6	353.2	0.75	0.531
Top_dressing	3	6291.7	2097.2	4.45	0.011
Basal_Fertiliser.Top_dressing					
	9	14313.3	1590.4	3.37	0.006
Residual	30	14144.2	471.5		
Total	47	37793.9			

Appendix 24: ANOVA table for the effect of Basal fertiliser and Top dressing on tuber diameter at the Zvimba site in the 2021/22 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	8.614	4.307	0.73	
Blocks.*Units* stratum					
Basal_Fertiliser	3	42.566	14.189	2.39	0.088
Top_dressing	3	83.213	27.738	4.67	0.009
Basal_Fertiliser.Top_dressing					
	9	128.127	14.236	2.40	0.035

Residual	30	178.004	5.933
Total	47	440.524	

Appendix 25: ANOVA table for the effect of Basal fertiliser and Top dressing on tuber yield at the Zvimba site in the 2021/22 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	812989.	406495.	6.37	
Blocks.*Units* stratum					
Basal_Fertiliser	3	747672.	249224.	3.91	0.018
Top_dressing	3	1003712.	334571.	5.24	0.005
Basal_Fertiliser.Top_dressing					
	9	4084097.	453789.	7.11	<.001
Residual	30	1914270.	63809.		
Total	47	8562741.			

Appendix 26: ANOVA table for the effect of Basal fertiliser and Top dressing on tuber length at the Chikombedzi site in the 2021/22 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	1152.3	576.1	1.84	
Rep.*Units* stratum					
Basal_Fertiliser	3	777.3	259.1	0.83	0.490
Top_dressing	3	4520.5	1506.8	4.81	0.008
Basal_Fertiliser.Top_dressing					
	9	6756.6	750.7	2.39	0.035
Residual	30	9404.4	313.5		
Total	47	22611.0			

Appendix 27: ANOVA table for the effect of Basal fertiliser and Top dressing on tuber diameter at the Chikombedzi site in the 2021/22 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	18.222	9.111	1.22	
Rep.*Units* stratum					

Basal_Fertiliser	3	47.206	15.735	2.10	0.121
Top_dressing	3	108.374	36.125	4.83	0.007
Basal_Fertiliser.Top_dressing					
	9	103.488	11.499	1.54	0.180
Residual	30	224.394	7.480		
Total	47	501.683			

Appendix 28: ANOVA table for the effect of Basal fertiliser and Top dressing on tuber yield at the Chikombedzi site in the 2021/22 growing season

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	47485.	23742.	0.77	
Rep.*Units* stratum					
Basal_Fertiliser	3	819122.	273041.	8.86	<.001
Top_dressing	3	1869757.	623252.	20.22	<.001
Basal_Fertiliser.Top_dressing					
	9	3298936.	366548.	11.89	<.001
Residual	30	924874.	30829.		
Total	47	6960174.			