Assessment of the performance of Maize (*Zea mays* L) intercropped with Jack bean (*Carnavalia ensiformis*) under subtropical conditions

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DECLARATION

I, Veronica Nomcebo Tumber, declare that the dissertation submitted to the University of Mpumalanga for the degree of Master of Science in Agriculture has not been previously submitted for any degree at this or any other institution. This dissertation in design and execution is my work and does not contain other people's graphs, pictures or data unless duly acknowledged.

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DEDICATION

I humbly dedicate this dissertation to my dearest brother, Dumsy Makhubela, my beautiful children, Sinenjabulo Tumber, Simucelile Tumber and Will Tumber. I extend my sincere gratitude to my husband Mr. M. Tumber, and to my parents Mr. W. Makhubela and Mrs. T. Masilela. I also wish to acknowledge my sister, Bongi Makhubela. Your loyal support, reassuring words, and relentless push for tenacity resonate deeply within me. You are the greatest family I could ever ask for, and I am forever thankful and proud of each of you.

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ABSTRACT

Food demand in Sub-Saharan Africa continues to rise, while soil fertility declines, climatic conditions remain uncertain, and farming systems rely heavily on chemicals. Sustainable cropping practices such as cereal legume intercropping are needed to address these challenges. This study therefore evaluated productivity of maize (*Zea mays* L) intercropped with jack bean (*Canavalia ensiformis*) under subtropical conditions of Mpumalanga Province, South Africa, to determine whether intercropping maize with jack could improve soil fertility and increase yield of maize. A randomized complete block design was used with sole maize, sole jack bean, and intercrop treatments. Growth and yield traits of both crops were measured, and soil samples were taken before planting and after planting. Seed quality were determined for protein, fat, fiber, and carbohydrate contents. One-way ANOVA and correlation analysis were used for comparisons. Intercropping markedly produced different outcomes across every growth and yield metric when compared with sole maize ($p < 0.001$). Specifically, intercropped maize demonstrated greater performance in various metrics, including protein content, chlorophyll content, plant height, stomatal conductance, leaf index, moisture content, and stem diameter. Intercropped maize had protein contents of 10.88% in season 1 and 8.12% in season 2, compared with 9.61% and 7.87% for sole maize in the same season. Furthermore, the intercropped treatment produced a land equivalent ratio (LER) exceeding 1, highlighting its efficiency in land use compared to monocropping. Intercropped maize averaged higher values across all yield components. Furthermore, cob length was 28.09 cm, kernel count averaged at 546.7 per cob, 100-seed weight was 0.5164 kg, and total seed weight amounted to 4.435 kg per block. Although yields declined in Season 2 due to drier conditions, intercropped maize still maintained an advantage with longer cobs (25.34 cm), more kernels (471.1 per cob), and higher seed weight (0.795 kg per block). Additionally, root nitrogen concentration was greater in intercropped maize than in sole maize during both seasons, intercropped roots averaged at 0.53% N versus 0.46% in sole maize in season 1, and 0.43% versus 0.40% in season 2. Additionally, intercropping maize with jack bean has significantly enhanced soil mineral nutrients, resulting in an average increase of 30kg N/ha in nitrogen, a 25% increase in phosphorus content and improved potassium stability. In addition, jack beans are underutilized, with no commercial varieties available and limited awareness among farmers. Research should focus on breeding adapted varieties, promoting its use in food and feed, and assessing its potential for poverty reduction.

Keywords: Maize, jack bean, intercropping, nitrogen fixation, soil fertility, food security, sustainable agriculture.

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LIST OF ABBREVIATIONS

Acronym	Full Meaning
AmAc	Ammonium Acetate
ANOVA	Analysis of Variance
APSIM	Agricultural Production Systems Simulator
Ca	Calcium
DMRT	Duncan’s Multiple Range Test
FAO	Food and Agriculture Organization
GY	Grain Yield
IITA	International Institute of Tropical Agriculture
K	Potassium
LAI	Leaf Area Index
LER	Land Equivalent Ratio
LSD	Least Significant Difference
Mg	Magnesium
N	Nitrogen
NPK	Nitrogen, Phosphorus, and Potassium
RCBD	Randomized Complete Block Design
SOM	Soil Organic Matter
SPAD	Soil Plant Analysis Development (chlorophyll meter reading
SPSS	Statistical Package for the Social Sciences

TDM	Total Dry Matter
WHO	World Health Organization
S	Season
W	Week

CHAPTER 1

1. INTRODUCTION

1.1. STUDY BACKGROUND

The growing global population creates substantial challenges for agriculture, compounding existing problems such as food-insecurity, land and water scarcity, soil degradation, biodiversity loss, and climate change (United Nations, 2019; IPCC, 2019; Alla-Kokko, 2021). Farmers are, therefore, obligated to utilize synthetic compounds such as chemical fertilizers to maximize productivity, while employing the use of chemical-based crop protection products (herbicides, fungicides and insecticides) to control insect-pests, weeds and diseases (Begam *et al.,* 2024). These products are often pricey, leading to higher production costs, thus, poor profitability (FAO, 2022). Groote and Gitonga (2021) reported that intense usage of chemical fertilizers and pesticides not only contributes significantly to environmental pollution but also links residues of these crop protection chemicals to human health risks

According to the United Nations (2020) projections, Africa's population is expected to rise from roughly 1.07 billion to about 1.40 billion by 2030 and could reach nearly 3.78 billion by 2100. This growth will push up demand for food and encourage more intensive agricultural methods, which in turn accelerate soil erosion, strip away nutrients, thus reducing soil fertility. (FAO, 2020). Furthermore, expanding agricultural land and intensifying farming practices can result in habitat damage and biodiversity loss (IPBES, 2019). Sustainable management of land, water, and soil quality is crucial for improving food security while adhering to planetary constraints (Groote and Gitonga, 2021; Weih and Tavoletti, 2022).

Glaze -Corcoran *et al*. (2020) reported that effective intercropping strategies are essential for sustainable resource utilization. Intercropping maize with crops like soy bean (*Glycine max*), common bean (*Phaseolus vulgaris* L) and bambara ground nuts (*Vigna suterranea*) has been historically adopted by both small-holder and commercial farmers, although these crops have been the subject of extensive research, a few underutilized legumes have received little attention in this regard (Brilhante *et al.,* 2021; Mustafa *et al.,*2021; Odesola *et al.,* 2023). Legumes fulfill multiple functions in intercropping systems, including biological nitrogen fixation, therefore, decreasing the use of synthetic fertilizers, increasing yields plus profitability while lessening environmental degradation (Brilhante *et al.,*2021; Shraddha *et al.*, 2024).

Neglected crops that tolerate drought and high temperatures, and resist pests and diseases, are well suited to agricultural systems with minimal external inputs in semi-arid and arid regions. (Ayilara, *et al.,*2022). Some underutilized crops have high nutrient content and can help diversify diets and alleviate nutrient shortages, particularly in rural communities (Pambuka, *et al.*,2022). Jack bean is among neglected indigenous legumes that possess advantageous traits which include adaptability to marginal soils and harsh climatic conditions *i.e.*, drought (Fritriani *et al.,*2024). Through the cultivation of maize intercropped with legumes, a significant increase in yield was observed, thus, land resource and water usage was improved (Chimoyo *et al.,*2020). However, there is little information on the efficacy of intercropping maize with jack bean. Furthermore, the effect of intercropping these crops on quality of the two crops has not been much reported under tropical rainfed conditions. This research seeks to close the gap in knowledge about how intercropping jack bean affects maize yield and quality, providing practical guidance for farmers, extension agents, and policymakers.

1.2. JUSTIFICATION OF STUDY

This study addresses the need for sustainable, space-efficient cropping in subtropical Mpumalanga by testing maize–jack bean intercropping as a way to boost yields, improve soil fertility, by fixing atmospheric nitrogen biologically, thereby lowering the need for synthetic fertilizers. Results will offer practical, locally relevant evidence for smallholders and planners seeking resilient, cost-saving cropping options.

1.2.1. Addressing food demand and population growth

Research by the United Nations (2020) reported that forecasts indicate Sub-Saharan Africa will see its population grow from 1.07 billion to near 1.40 billion by 2030. The increased demand for food resulting from this population shift puts tremendous strain on the current agricultural systems. This demand cannot be satisfied by traditional agricultural. methods alone, so new cropping systems that can increase yield without sacrificing environmental integrity must be investigated (Godfray and Garnett, 2020).

1.2.2. Declining Soil Fertility

According to Vanlauwe and Giller (2020) many areas, including Mpumalanga Province, diminishing fertility and soil degradation are major obstacles to agricultural output. Crop yields are negatively impacted by nutrient depletion brought on by continuous monocropping, especially of staple crops like maize. Through biological nitrogen fixation, intercropping systems, especially those that include legumes like jack beans can increase soil fertility, reduce adverse impacts of nutrient loss and boost soil condition (Mazzoncini and Barberi, 2020).

1.2.3. Climate Change and Environmental Sustainability

Agricultural production is highly affected by climate change, which causes erratic weather patterns, higher temperatures, and more frequent droughts (Lobell and Schlenker, 2011). These modifications put smallholder farmers' livelihoods at risk and worsen food insecurity. By maximizing resource utilization, enhancing moisture retention, and lowering reliance on chemical fertilizers which increase greenhouse gas emissions, intercropping provides a sustainable agricultural technique that can improve resilience to climatic unpredictability (Tittonell and Giller, 2013).

1.2.4. Nutritional Quality and Food Security

Despite being a staple crop in many rural communities, maize frequently lacks important minerals and protein (Muthoni and Muthoni, 2020). Intercropping with jack bean, which is high in protein and other essential nutrients, can considerably increase the extent to which the food supply meets nutrient needs (Osei, 2020). This is particularly important in at-risk communities for enhancing food diversity and addressing undernutrition. (Keston *et al.,*2021; Maposa and Jideani, 2027; Kerr *et al.*, 2007).

1.2.5. Economic Viability for Smallholder Farmers

Due to their reliance on chemical fertilizers and other inputs, smallholder farmers tend to deal with high production expenses (Tittonell, 2014). By organically boosting soil fertility and reducing input requirements, intercropping systems can cut these costs while also increasing overall yield per unit area (Vandermeer, 2010). Since small-scale producers are often the foundation of food supply in developing nations, increased earnings play a key role in elevating their standard of living.

1.2.6. Underutilization of Indigenous Legumes

According to Rojas and Ochoa (2020) jack bean is an underutilized legume often called forgotten legume that has significant potential to agricultural production in South Africa. Despite its benefits, it remains largely neglected in research and development (Singh and Singh, 2020). The study’s objective is to fill outstanding informational voids regarding jack bean's role in intercropping systems, promoting its utilization and integration into mainstream agricultural practices.

1.2.7. Contribution to Sustainable Development Goals

The results from this study support the Sustainable Development Goals (SDGs) of the United Nations, especially Goal 2 (Zero Hunger) and Goal 13 (Climate Action) (United Nations, 2015). The study supports larger initiatives to accomplish these global goals by showcasing the potential of jack beans in improving food security thus encouraging sustainable agriculture (FAO, 2020). In summary, the imperative to develop sustainable agricultural practices that enhance food security, restore soil health thus improving the economic viability of farming systems particularly under pressures from population growth and climate change provides strong justification for this study. A viable alternative that merits more research and application is the intercropping of maize and jack beans.

1.3. PROBLEM STATEMENT

Global population continues to grow, exerting increasing pressure on food systems and driving a rising demand for agricultural production. However, agricultural production is struggling to keep up with this growing demand, resulting in a shortfall in food supply. This shortage is attributed to higher summer temperatures and minimal rainfall, which had led to lower yields and poor quality crops, ultimately impacting both domestic consumption, food security and exports (Groote and Gitonga, 2021). Maize serves as the essential dietary staple for countless individuals across sub -Saharan Africa thus serves a vital role in ensuring food security for many households across rural areas. A significant factor contributing to the low yields of maize in these regions is the deterioration of soil fertility, most soils where maize is cultivated lack the necessary nutrients. Farmers often plant maize consecutively without restoring the soil's nutrients levels. As a result, key nutrients such as nitrogen, phosphorus and potassium, vital for the maize growth and productivity becomes depleted (Giller,2001). This depletion leads to stunted crop growth, reduced grain production and ultimately contributes to food shortages.

The IPCC (2019) found that climate changes can significantly affect crop cycles and interactions between plant species. However, intercropping systems can regulate climate, optimize soil moisture, maximize solar radiation, lower greenhouse-gas output, enhance carbon storage, and boost overall sustainability. Cultivating maize with commercialized legumes (soybean) and underused legumes such as bambara ground nut which yielded positive results in both yield and quality, however in the case of intercropping with jack bean remains relatively under researched. Furthermore, jack bean production is commonly associated with smallholder farmers and women as primary producers and processors. Jack bean production is limited due to a lack of understanding regarding improved cropping systems, agronomic methods, processing, and utilization (Fitriani *et al*., 2024).

1.4. PURPOSE OF THE STUDY

1.4.1. Aim

This study aims to evaluate the performance of maize when intercropped with jack bean under subtropical conditions in Mpumalanga province, South Africa, focusing on the effects on maize growth, yield, quality, soil fertility in comparison to monocropped maize.

1.4.2. Objectives

1. To assess the impact of intercropping maize with jackbean on maize growth and yield.

2. To examine the effects of intercropping maize with jack bean on maize quality and the mineral nutrient content of the soil.

1.4.3. Hypotheses

The following research questions direct this study:

1. How does intercropping maize with jack bean influence the growth and yield of both crops compared with sole cropping systems?
2. What changes occur in soil mineral nutrient concentration when maize is intercropped with jack bean compared to monoculture?

Hypothesis in null format for testability and falsifiability:

H1: Intercropping maize with jack bean produces a significant difference in the growth and or yield of one or both crops compared with monocropping.

H2: Soil mineral nutrient concentrations differ significantly in maize jack bean intercrops compared with sole maize systems.

1.5. RELIABILITY, VALIDITY, AND OBJECTIVITY

1.5.1. Contribution to food security

Food insecurity continues to pose a major challenge in Sub-Saharan Africa. According to FAO (2020) the rising levels of hunger can be attributed to increasing population pressures and climate related stresses. In South Africa maize is the primary staple, however, it is lacking in protein and essential nutrients necessary for balanced diet, one potential solution to this nutritional deficiency is to intercrop maize with jack bean, whose seeds are high in protein and carbohydrates (Fritriani *et al*., 2024). When incorporated with maize in meals, they enrich dietary composition and mitigate malnutrition risks. For smallholder farmers, this method provides a safety net, even in years when maize yields are low due to drought, they can still harvest jack beans for their nutritional needs. Overtime, intercropping can enhance household nutrition and strengthen food security (Muthoni, 2020).

1.5.2. Climate change adaptation and mitigation

Climate change has significantly impacted agriculture in South Africa, leading to higher temperatures, erratic rainfall patterns and more frequent droughts (IPCC, 2019). Farmers who rely on rainfed crops are particularly at risk, as these unpredictable weather conditions can result in reduced crop yields, increasing vulnerability to pest and diseases and ultimately threaten food security. Intercropping presents a climate resilient strategy that mitigates these risks by allowing the cultivation of multiple crops on a single farm (Chimoyo *et al*.,2020). Jack bean as an intercrop promotes the overall resilience of agricultural system, improving its capacity to cope with adverse conditions. Furthermore, jack bean contributes to nitrogen fixation, which decreases the reliance on synthetic fertilizers that are known to emit greenhouse gases. This dual benefit not only helps combat climate change but also enhances the adaptive capacity of farmers

1.5.3. Economic benefits to smallholder farmers

Small-scale farmers often face high operational expenses due to their reliance on fertilizers and pesticides (Hong *et al*.,2019). However, intercropping jack beans with maize can help lower these costs, as the nitrogen provided by the legume reduces the need for purchased fertilizers. Additionally, farmers benefit from harvesting both jack beans and maize from the same plot of land. This practice enhances land use efficiency, which can be evaluated using the Land Equivalent Ratio (LER). Studies indicate that intercropping typically yields LER values greater than one, signifying higher productivity compared to monoculture cropping (Chunjie *et al*., 2023). For smallholder farmers, this approach is crucial for improving profitability and ensuring food availability. Ultimately, this system represents a low input, cost -effective strategy that is economically viable.

1.5.4. Promotion of underutilized indigenous crops

Research and development efforts are currently focusing on underutilized indigenous legumes such as cow pea and bambara groundnut. However, jack bean remains one of the least studied legumes, despite its hardiness and nutritional benefits (Mustafa *et al*., 2021). Promoting jack bean through intercropping research is essential, as it not only improves cropping system but also enhances food diversification. Additionally, these underutilized legumes contribute to agricultural biodiversity and are often more resilient to pests, diseases and climate related stresses (Mudau *et al*., 2022). This investigation highlights jack bean's value as an integral part of sustainable agricultural practices within South Africa.

1.5.5. Scientific contribution

Scientifically, the research addresses an existing knowledge shortfall on maize–jack bean intercropping. In South Africa, intercropping with cowpea and soybean has been adequately researched, while jack beans have received less attention. This study offers insights into soil chemical changes, crop physiology, and yield in maize and jack bean systems. It also contributes information on nitrogen fixation and land productivity under subtropical conditions. These conclusions supply a solid information base that extension personnel, academics, and policymakers can use to recommend effective farming systems.

1.5.6. Contribution to Sustainable Development Goals

By increasing yields and producing more protein-rich food, this research supports SDG 2 (Zero Hunger). It also advances SDG 13 (Climate Action) by promoting practices that can lower emissions and bolster farming resilience to climate variability. Overall, the findings contribute to sustainable food systems that balance productivity, environmental stewardship, and farmer livelihoods, in line with the UN 2030 Agenda (2015).

1.5.7. Policy relevance

The outcomes of this research have direct policy relevance. If maize jack bean intercropping is shown to be effective, policymakers can promote it as a recommended practice for smallholder farmers. Agricultural extension programs can use the findings to provide training on intercropping techniques. Policies could also encourage seed availability for jack bean and support farmers with resources for implementation. This can help integrate indigenous legumes into national agricultural strategies.

1.6. Bias

This research evaluated how well maize and jack bean perform when grown together under subtropical conditions in Mpumalanga Province, South Africa. Field-based experiments were carried out at Makhundu Farm in Nkomazi district to compare sole and intercropped maize.

The measured outcomes included maize development and yields, jack bean production, changes in soil nutrient status, and crop quality metrics (protein, fat, fiber and carbohydrate). Additionally, study also examined root nodulation as an indicator of biological nitrogen fixation and utilized the land equivalent ratio to evaluate land-use efficiency.

The trial was conducted at a single experimental location over one cropping season, with intentions to repeat it the following season. The trial tested just one maize cultivar hybrid white and one white jack bean accession. Only three treatment options were included: maize monoculture, jack bean monoculture, and maize intercropped with jack bean; no other legume species or intercrop arrangements were evaluated. Rainfall, temperature and humidity were recorded only throughout the trial period. A comprehensive economic profitability assessment was not performed, however discussions highlighted potential economic advantages such as lower input needs and more efficient land use.

To reduce experimental bias, treatments were randomized and replicated so that random error was minimized. Because the trial was limited in location, duration, and genetic/treatment diversity, the results should be extrapolated to other regions, cultivars, or longer-term systems with caution. Nevertheless, the findings provide practical, context-specific guidance for smallholder farmers and agricultural planners while underscoring the need for multi-site and multi-season validation before wider adoption.

1.7. SCIENTIFIC SIGNIFICANCE OF THE STUDY

Climate change impacts subtropical regions through high temperatures, droughts, irregular rainfall, and floods, thus reducing crop productivity. Furthermore, crop yields depend heavily on climate and can be disrupted by their variability and the changes in abiotic factors can significantly influence crop growth productivity (Billah *et al.,* 2021). However, intercropping is a sustainable agricultural practice that promotes biodiversity, improving soil fertility, and enhancing ecosystems. Specifically, intercropping maize with jack bean can help mitigate climate change, reduce the use of synthetic fertilizers, improve soil fertility while also lowering carbon emissions (Zhang and Li, 2020). Intercropping maize and jack bean is essential for enhancing crop diversity and resilience, particularly in these changing environmental conditions (Altieri, 2018). The study's conclusions will enable small-holder farmers to make wise choices, enhancing their standard of living and promoting a more sustainable food system. Additionally, this study will provide farmers, policy makers, and extension agents with useful information. Evaluating maize intercropped with jack bean under subtropical conditions, the study identifies ways the system can enhance yield performance, soil fertility, and overall sustainability.

1.8. STRUCTURE OF THE DISSERTATION

The order of presentation of the dissertation is:

I. **Chapter One** – Introduction: gives context information, states research problem and presents the study aim, objectives, research questions, hypothesis, significance, scope and delimitations.

II. **Chapter Two** — Literature review: Overview of intercropping systems, ecophysiology of maize–legume interactions, nitrogen-fixation mechanisms, and jack bean agronomic/nutritional attributes

III. **Chapter Three** – Methodology: The study setting experimental arrangements and methods, methods of data collection, sampling, analytical methods and statistical methods are outlined

IV. **Chapter Four** – Results interpretation and discussions: reports and interprets findings on maize growth and yield, jack bean performance and changes in soil mineral nutrients and nutritional quality analysis.

V. **Chapter Five** – Conclusions and Recommendations: Summarizes principal findings, draws conclusions, provides practical recommendations for farmers and policymakers, and suggests avenues for future research

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CHAPTER 2

2. LITERATURE REVIEW

2.1. INTRODUCTION

Global population is anticipated to be at about 9.7 billion in 2050, prompting a projected 50% increase in food demand. However, agricultural production is expected to struggle to match this escalating demand, leading in shortage of food supply. To address this gap, agricultural output must increase by over 70% (United Nations, 2021). Furthermore, rising summer temperatures and limited rainfall have resulted in lower crop yields and diminished quality, this will result in negative effect on local consumption, food security, and export capacity. Food insecurity in poor countries is caused by overpopulation, natural calamities, insufficient food distribution, and low food production levels (FAO, 2020). Effective resource management in South Africa, such as land, water, and soil quality, has the potential to dramatically improve food security while maintaining within planetary limitations. Sustainable food systems can assist alleviate these issues by aligning food and nutrition security objectives with environmental protection and climate mitigation strategies (Groote and Gitonga, 2021).

Climate change exacerbates poor food production levels; for example, the Intergovernmental Panel on Climate change (2019) stated that it may have adverse effects on crop cycles and natural plant interactions. Nonetheless, intercropping systems can help combat climate change by retaining soil moisture, providing ground cover, optimizing solar radiation collection, lowering greenhouse gas emissions, increasing carbon sequestration, and promoting sustainability (Huss *et al*. (2022). Although intercropping has been done for generations, its advantages have not been fully realized. Recent research has concentrated on intercropping maize with both commercial legumes like soybean and underutilized legumes like Bambara ground nut, cowpea, and peanut, which has resulted in positive economic returns and nitrogen fixation, reducing fertilizer requirements (Ngwenya *et al*., 2024). Nonetheless, jack bean remains underexplored, and it is frequently connected with smallholder farmers and women, who play important roles in agriculture in many African countries. Women produce and process a major number of crops, especially indigenous legumes such as jack beans. FAO (2023) indicates that women produce about 60–80% of the food in many impoverished nations and nearly 50% worldwide; their work has only recently been more widely recognized. Constraints in production often arise from inadequate knowledge of improved cropping systems, agronomic methods, and processing technologies (Fitriani *et al*., 2024). Maize intercropped with common beans has long been popular among both small and commercial farmers. However, according to Brilhante *et al*. (2021), a limited number of indigenous underused cultivated crops have been properly explored. According to Shraddha and Bhardwaj (2024), legumes are essential in intercropping systems because they help with biological nitrogen fixation, boosts soil quality, lessen dependence on chemical fertilizers, increase yields, and encourage functional diversity. When used as cover crops, legumes help retain soil moisture and can reduce the need for irrigation. Underutilized species that tolerate drought and high temperatures and resist pests and diseases are especially appropriate for low-input farming in semi-arid and arid zones (Ayilara *et al*., 2022).

Originating in Central and South America, jack beans are grown both for human consumption of its seed and as animal fodder. Jack bean's potential to fix atmospheric nitrogen makes it common soil covering crops or intercrop used to enrich soil fertility and raise the productivity of companion crops like maize. Legume such as this has been traditionally utilized, especially in tropical and subtropical regions, as it aligns with sustainable agricultural practices. Research by Sangakkara *et al*. (2019) indicates that jack bean's growth characteristics complement those of maize, leading to improved resource utilization, its vining habit lets it occupy vertical space, cutting down on competition for light and taking advantage of the structural support offered by maize. Adesina *et al*. (2022) reported a 30% increase in water use efficiency for maize cultivated alongside jack beans, which is particularly advantageous in drought-prone areas. Jack bean is resilient, thriving in poor soil conditions and drought-sensitive environments. With its extensive root system, jack bean can draw water and nutrients from deeper soil horizons, making it a valuable component of intercropping systems. Huss *et al*. (2022) defines intercropping as the cultivation of multiple crops within a single field over a growing period, promoting resource diversification through complementary use of water, sunlight, and nutrients. Moreover, Intercropping is also regarded as a low-cost way to improve environmental and climate resilience by reducing chemical use. Growing interest in sustainable agricultural practices has renewed focus on jack bean as a highly effective intercrop with potential to raise yields. Its excellent nitrogen-fixing capacity adds to soil fertility, with intercropping jack beans and maize enhancing soil nitrogen levels, which positively influences subsequent maize growth and production (Ojo *et al*., 2021).

Zhang *et al*. (2021) discovered that intercropped systems produced 25% more maize than monoculture, owing to nitrogen inputs from jack beans. Furthermore, intercropping maize and jack beans can help with pest and disease management since the coexistence of various plants disrupts pest life cycles and reduces population growth. Mazzoncini *et al*. (2023) discovered that maize intercropped with jack beans exhibited less pest damage than maize produced in monoculture, owing to the diversity effect. Jack bean is also known for attracting beneficial insects that help to control pest populations, resulting in healthy maize fields. Intercropping maize with jack beans enhances nutritional quality of maize. Research indicates that maize grown alongside legumes exhibits higher protein content, with Ojo *et al*. (2021) confirming that intercropped maize grains had 15% more protein than those from monoculture. This enhancement is linked to the nitrogen supply from jack beans, essential for nucleic acid synthesis in proteins. Furthermore, intercropping maize or other crops with jack beans improves grain quality, such as kernel size, weight, and texture. As shown in their work Adesina *et al*. (2022), intercropped maize grains had improved grain yield, as seen by greater bigger grain size and bulk density, which was ascribed to better soil conditions and nitrogen supplied by jack beans. Despite the numerous studies on intercropping (Table 2.1), few have focused on maize and jack beans, and other underutilized legumes, which provide the basis for this article review

Table 2.1: Previous reviews on the yield evaluation of maize intercropped with Jack bean and other legumes			
Topic	**Objective**	**Contribution**	**Reference**
Analysis of Maize-Based Intercropping Systems	To study the existing findings on maize intercropping system and the effect in terms of efficiency of productivity and land use.	The literature review shows that intercropping enhances production by better utilizing resources, as measured by the Land Equivalent Ratio (LER). It also reduces pests, diseases, and climate fluctuations, as well as competition with weeds. Study gaps are highlighted in relation to research opportunities for the development of intercropping studies to address intercropping for food security and other agricultural fields for sustainable agriculture.	(Seran & Karunarathna, 2010).

Examination of Maize-Legume Intercropping to Enhance Productivity and Soil Fertility within practices of Sustainable Agriculture in India.	To evaluate the efficacy of maize-legume intercropping against decreased farmland and the increasing pressure for a growing population in India.	The review looks at how maize-legume systems assist to boost yield stability, improve soil nitrogen levels through nitrogen fixation, and maximize overall resource utilization. It proposes that these systems not only preserve yields but also improve soil health and biodiversity, making them a promising solution to sustainable agriculture operations. Maize intercropped systems provide a comprehensive strategy for sustainable agriculture by increasing yield consistency, enhancing soil nitrogen through the process of nitrogen fixation, and maximizing the efficient use of resources. These systems not only maintain productivity but also contribute to improved soil health and biodiversity, making them a viable	(Ananthi *et al.,*2017).

		option for promoting sustainable farming practices	
Evaluation of the Effects of Maize-Legume Intercrops on the Diversity and Population Dynamics of Entomophagous and Phytophagous Insects.	To measure the impact of intercropping on the population of insects, both advantageous and detrimental, and its potential as an ecological pest management method.	Maize-legume systems attract beneficial insects, which, according to the research, are a major part of pest management practices, including predators and parasitoids. It identifies certain legume species that enhance these beneficial interactions and argues that intercropping can enhance integrated pest management strategies while promoting ecological balance.	(Pierre *et al.,*2023).

Assessment of the Productivity of Maize Intercropping Systems.	To evaluate how the addition of legumes into maize systems leads to better yield, soil fertility, and resource efficiency in the context of land and food scarcity.	This overview highlights how maize-legume combinations enhance yield, nitrogen fixation, and soil quality. It demonstrates that crop compatibility, spacing, and planting time affect performance and are measured using the Land Equivalent Ratio (LER) and Area Time Equivalent Ratio (ATER).	(Manasa *et al.,*2020).
Potential of Underutilized Food Legumes in Meeting Pulse Requirements in India – A Review.	To address the contribution of underutilized legumes - horse gram, rice bean and jack bean – to expanding agricultural practices and food systems.	The review highlights the drought tolerance and nutrient-dense advantages of these legumes versus conventional crops. It shows their power to relieve hunger and urges for further national food and feed systems to be integrated.	(Palai *et al.,*2019).

Review on Exploring the Potential of Maize-Legume Intercropping Systems for Agricultural Sustainability.	To study the productivity and environmental benefits that maize-legume intercropping offers and to recommend alternative sustainable resource utilization.	The study demonstrates that intercropping increases yields, optimizes nutrient and water use, and improves soil conservation through greater ground cover. It also outlines the recommendations for crop combinations that are suitable for planting.	(Sahoo *et al.,*2023).
A Systematic Review: Can Cereal-Legume Intercropping Systems Enhance Household Nutrition in Semi-Arid Environments?	Ameta-analysis technique to investigate intercropping solutions to optimize nutrition and sustainable agriculture in water-limited locations.	The study introduces nutritional water productivity, which links water consumption with nutrient yield. It challenges the assumption that higher yields are the sole guarantee of nutritional security and calls for a re-evaluation of food systems from both agronomic and nutritional perspectives.	(Chimonyo *et al.,*2023).

Review of the Nutritional, Functional, and Bioactive Properties of Underutilized African Legumes.	To investigate the nutritional, functional, and bioactive aspects of neglected African legumes.	Researchers investigated crops such as Bambara groundnut, Adzuki bean, and African yam bean due to their high nutritional value and positive health effects. It advocates the development of policies and research schemes to promote their use and integration into mainstream food systems to tackle malnutrition.	(Popoola *et al.,*2023).
Review of Underutilized Legumes: Uncovering the Untapped Benefits for Agriculture, Nutrition, and Environmental Sustainability.	To assess the potential of underutilized legumes for the improvement of agricultural production, nutrition, and environmental health.	The review addresses the role of these legumes in enhancing food security and ecological resilience. What it identifies include key barriers, namely low yields, market neglect and inadequate policy support, with a few specific approaches that may be tailored, particularly through farmer education and supply chain improvement measures, it notes.	(Odeku *et al.,*2024).

A Review: Enhancing Soil Quality through Legume-Based Intercropping Systems.	To assess how legume-based systems contribute to the improvement of soil's chemical, biological and physical properties.	The review presents evidence that combining legumes with cereals enhances soil fertility, moisture retention and resource use efficiency. It highlights the necessity to systematically compare with monocropping systems in order to detect long-term effects in terms of soil health.	(Sagar *et al.,*2024).
Review on Bridging the Yield Gap of Maize in Southeast Asia through Intercropping Systems.	To analyze the restrictions of maize productivity and to examine intercropping as a remedy.	This review shows how companion cropping improves land utilization, reduces erosion, and reduces the need for fertilizers. It emphasizes how proper crop timing, spacing and choice need to be in place to achieve a Land Equivalent Ratio (LER) of greater than one. It also acknowledges the scarcity of information about the benefits of	(Khongdee *et al.,*2022).

		nitrogen fixation under specific regional conditions.	

2.3. MORPHOLOGICAL TRAITS AND BIOMASS ACCUMULATION OF JACKBEAN ACROSS GROWTH STAGES

Jack bean is a popular bush in tropical and subtropical climates for plant and soil amendment. It is classified as a stress tolerant plant that grows well in diverse soil types, which is a great use for different farming methods. Over 120 days cycle, jack bean produces more than 40 t/ha of green biomass and above 4-8 t/ ha of dry mass (Carnier *et al*., 2022). According to Prasojo *et al*. (2025), jack bean forage yields differ with stage of growth as they show that the pod stage providing freshest fodder gives up to 43.23 tons per hectare. This is considerably greater than the output of vegetative stage (19.39 t/ha) and flowering stage (34.35 t/ha). During the pod growth stage, the new leaf and stem growth reached 22.51 and 20 t/ha respectively. Findings indicate pronounced morphological traits of jack bean in this important stage accompanied by considerable biomass accumulation.

According to Armaji *et al*. (2025), the growth and development of jack bean can be improved greatly through application of boron and arbuscular mycorrhiza. According to their results, combining 46 mg/l of boron with 5cm Miko-SC yielded the greatest increase in plant height, stem thickness, and leaf breadth, which is indicative of favourable vegetative development. The best breeding environment mixed 23 mg/l of boron and 6cm of Miko-SC was the most favourable conjunction which yielded the largest number of leaves, pod weight, and grain weight. These results provide evidence for the influence of boron and arbuscular mycorrhiza on jack bean growth characteristics during development. The findings indicate that the purposeful use of boron and Miko -SC can greatly improve quality of jackbean production.

2.4. INTERCROPPING AS A SUSTAINABLE APPROACH AND BENEFITS OF INDIGENOUS LEGUMES

Cultivating two or more crops together at the same time (intercropping) has been widely examined because it can boost soil organic matter and elevate crop yields. According to Wang *et al*. (2020), planting multiple crops together substantially boosts soil organic carbon through the broad root systems and added biomass of the component species. For example, Zhang *et al*. (2021) discovered that long-term intercropping can improve soil organic matter content by 10-25% when compared to monoculture systems. Such gains are important as they improve soil texture and water-holding capacity while enhancing nutrient supply, resulting in higher harvests. Furthermore, Li *et al*. (2020) observed that combining legumes with cereal in an intercropping system can result in a 15-30% boost in production over monocropping systems.

Zhang *et al*. (2022) conducted a review that found that intercropped systems outperformed monocultures, with yield improvements ranging from 20-40%, particularly in poor soils where the benefits of added organic matter are more apparent. These findings support the positive relationship between soil organic matter and crop output, implying that intercropping improves both soil health and agricultural productivity.

Research indicates that growing crops together is a highly effective way to increase yields and build soil organic matter, supporting more sustainable farming systems (Brannan *et al*., 2023). Yet many legume species, which offer strong nutritional, environmental, and economic benefits, are still largely overlooked in commercial agriculture (Brilhante *et al*., 2021). High in protein, dietary fiber, and essential micronutrients such as iron, zinc and B-group vitamins, these legume crops can broaden food options and help reduce micronutrient malnutrition, particularly in low-income regions. Furthermore, their low glycemic index makes them appropriate for diabetic individuals (Ayilara *et al*., 2022). Underutilized legumes improve soil fertility through biological nitrogen fixation, lowering dependence on synthetic fertilizers and supporting sustainable agricultural systems. Furthermore, these forgotten legumes promote biodiversity within ecosystems, resulting in agroecosystems with enhanced climate resilience and disease outbreaks. Economically, they create opportunities in the health-food market and let farmers diversify production to raise incomes. Furthermore, promoting these underutilized legumes helps to improve social welfare, food security, and cultural heritage preservation while also encouraging sustainable agricultural systems (Chimoyo *et al*., 2020).

Intercropping maize reduces soil erosion and surface runoff while helping to preserve the quality of topsoil. Consequently, fertilizer application levels in maize intercropping systems tend to be lower, which can mitigate environmental issues in downslope regions. Coelho *et al*. (2024) found that when jack beans were cultivated alongside maize, they achieved higher phytomass and nutrient uptake, resulting in a 23.0% increase in maize grain yield over two growing cycles. However, the study also highlighted challenges associated with jack beans, including their vulnerability to whiteflies, which can transmit various bean viruses. Additionally, Darini *et al*. (2022) noted that jack beans can host root-knot nematodes, which can compromise their suitability in fields already infested with these pests. While jack beans offer significant agronomic and nutritional benefits, careful management practices are essential to maximize their potential. This includes implementing integrated pest management strategies to mitigate threats from pests like whiteflies and root-knot nematodes, which can adversely affect crop health and productivity. Understanding the soil and climatic conditions optimal for jack bean cultivation can further enhance their growth and nutrient utilization, ultimately improving overall productivity and sustainability in intercropping systems (Brannan *et al*., 2023).

Jack bean intercropping is especially beneficial on feral soils with a clay texture, as research has shown that jack beans improved aggregate stability in the upper 0–20 cm of soil and reduced penetrometer resistance, thereby improving soil structure and aeration (Moura *et al.,* 2021). Furthermore, jack beans, whether cultivated as cover crops or intercropped with maize, successfully reduce soil erosion in feral soils of similar texture. Monitoring soil quality indicators and conducting soil quality index studies might be useful methods for measuring the impact of jack bean management systems on producing high- producing crops (Pereira dos Santos *et al*., 2021). Rani *et al*. (2022) stressed the benefits of rotating legumes with maize, pointing out that this technique not only restores nutrients but also promotes succeeding crops, lowering production costs and increasing sustainability without sacrificing yields. Ávila *et al*. (2023) found no significant changes in grain output across inoculation parameters with different green manure sources. However, non-inoculated treatments using jack beans resulted in a substantial yield increase of maize 14 bags per hectare. These findings suggest that beneficial associative bacteria may enhance root system development and nutrient uptake, leading to increased crop yields. Thus, it can be stated that intercropping, particularly when combined with beneficial bacterial inoculation, could prove effective to significantly boost yields and contribute to more sustainable agricultural practices. Additional studies highlighting the benefits of intercropping can be found in Table 2.2 below.

Table 2.2: Previous key findings on yield evaluation of maize intercropped with jack bean			
Topic	**Objective**	**Contribution**	**Reference**
The Impact of Intercropping Maize and Jack Bean on Growth and Yield.	The study examine the growth and yield of maize intercropped with jack beans	For maize yields, intercropping systems greatly improve over monoculture through higher resource utilization and reduced weed competition. Intercropping maize and jack beans increased overall returns by 30% and profit margins by 40% as inputs were reduced, according to the study.	(Nwako, 2021)
The effect of Intercropping on Growth Parameters: A Comparative Analysis of Crop Performance.	The study assess how intercropping affects growth parameters and yield performance.	Jack beans are significantly influential on maize growth metrics, such as plant height and biomass, resulting in a 25% increase in yield when compared to monocultures. Their nitrogen-fixing ability increases nitrogen absorption by 30%, enhancing	(Ojo *et al.,* 2021 ; Khan *et al.*, 2022)

		plant growth and tolerance in dry conditions.	
Nutritional Quality and Grain Composition of Maize Intercropped with Jack Beans.	To investigate the impact of intercropping maize with jack bean on the nutritional quality of maize grains.	Maize grains grown in intercropped systems contain 15% more protein than those grown in monoculture. According to another comparison study, intercropping maize with jack beans produced 20% higher biomass than monoculture. Moreover, this study observed a 15% improvement in land use efficiency, which demonstrates that this approach is successful for achieving more per unit area	(Adebayo & Ogunbayo, 2023)
Physical Quality of Growth Parameters in Maize Intercropped with Jack Beans.	To investigate the impact of intercropping maize with jack bean on the physical quality indices of maize grains	Maize grains cultivated in intercropped systems exhibited superior physical qualities such as larger kernel diameters and test weights.	(Adetunji *et al.,*2022)

Pest Management Strategies in Maize Intercropped with Jack Beans.	To assess the effectiveness of jack beans in controlling pests in maize production.	Intercropping is reported to reduce the incidence of insects, create a healthier crop ecosystem, and decrease the demand for chemical pesticides.	(Tchokponhoue & Yao, 2023)
Evaluating the Effects of Jack Bean Intercropping on maize productivity	To measure maize productivity and soil health indicators (nitrogen content, microbial activity, etc.) at the level of maize and jack beans mixed in intercropping.	The results indicated the impact of intercropping on maize yield and soil health as significant compared to monocropped system	(Karanja & Mwangi, 2022)
Investigating Sustainable Intercropping Systems	To assess the feasibility of intercropping maize and jack beans for sustainability based on resource	The research found that intercropping is expected to lead to resource optimization and economic benefits	(Ochieng & Njeru, 2023)

with Maize and Jack Bean.	utilization efficiency and economic viability.		
Nutrient Dynamics and Their Implications in Maize Intercropped with Jack Beans.	To investigate the impact of intercropping maize with jack beans on nutrient absorption and soil nutrient dynamics	Jack beans enhanced maize nutrient availability; in return it was found to have good growth and productivity supporting integrated nutrient management approaches.	(Menda & Kisaka, 2023)
The Effects of Intercropping Maize with Legumes on Soil Fertility and Crop Productivity.	Examining how intercropping maize with legumes, especially jackbean has influenced soil nutrient levels and maize yield	The research highlighted the significance of intercropping in improving soil fertility through biological nitrogen fixation and increasing maize production.	(Bationo *et al.,*2020)
The Impact of Intercropping on Photosynthetic	To examine photosynthetic rates and total yield changes arising out of intercropping maize with jack bean		(Rawat & Kumar, 2021)

Performance and Yield of Maize.	from various species and to evaluate its impacts	The research observed that intercropping enhances photosynthetic efficiency and maize productivity compared to crops grown in monoculture	
The Relationship Between Chlorophyll Content and Crop Yield in Intercropped Systems.	To find out the effect of maize intercropping (maize intercropping/jack bean farming) to control chlorophyll content in relation to maize yield	The data showed that higher concentration of chlorophyll in intercropped maize and thus yield suggests that intercropping enhances light-harvesting and photosynthesis efficiency for the plants.	(De Souza *et al.,*2024)
The Impact of Intercropping Jack Beans on Stomatal Conductance in Maize.	To examine the impact of intercropping maize with jack beans on stomatal conductance and efficiency of water use.	The study found that under mixed crop intercropping the stomatal conductance and water usage efficiency is better, due to jack bean intercropping. This can help improve the yield as plants are able to optimize water uptake and photosystems.	(Mwangi *et al.,*2023)

The Variability of Stomatal Conductance in Maize Intercropped with Jack Beans Under Drought Conditions.	To study how drought stress affects the stomatal conductance of maize intercropped with jack beans.	Intercropping maize and jack bean improves stomatal conductance in maize thereby improving water use efficiency. Maize with jack beans is intercropped in a way that holds stomatal conductance to be better under drought stress than it is in monoculture systems.	(Tchokponhoue & Yao, 2023)
Morpho-Physiological Changes in Maize Induced by Cover Crop Rotation in Northern Brazil.	To assess maize produced in succession with cover crops, both physiological and the productive.	Maize provided better field performance when intercropped with Jack bean relative to other cover crops and jack bean also increased moisture holding capacity and decreased soil temperature,	(Souza *et al.,*2024)

2.5. MECHANISMS ASSOCIATED WITH INTERCROPPING CONTRIBUTE TO ACCUMULATION OF ORGANIC MATTER

Mixed cropping is a commonly used agricultural method that increases soil organic matter, thereby boosting fertility and overall soil health. This practice boosts organic matter production by diversifying root systems through the cultivation of different crops. The diversity in root structures contributes to increased microbial diversity, better soil clumping and the soil's ability to hold organic material. According to Zhang *et al*. (2023), intercropping maize with legumes leads to greater root biomass, which in turn improves soil structure and promotes organic matter accumulation. Additionally, intercropping often produces greater total biomass than monocultures, enhancing the incorporation of organic materials into the soil. According to Ofori and Stern (2022) mixed-crop systems can increase total biomass by up to 30%, thereby supplying more organic matter to the soil.

Furthermore, intercropping enhances nutrient cycling and thereby supports formation of soil organic matter. Companion species tap different nutrient pools, which lowers losses and improves resource use. Waqas *et al*. (2023) found that cereal–legume mixtures speed up nitrogen turnover, enhancing residue decomposition while promoting accumulation of organic matter in the soil. Mixed cropping also has a favorable impact on microbial activities, for example, plant species diversity can increase the richness and activity of microbial communities, boosting organic matter breakdown and stabilization.

Liu *et al*. (2023) discovered that intercropping boosts microbial activity and biomass while also improving organic matter stability through the synthesis of microbial-derived organic compounds. Assefa *et al*. (2022) also point out that intercropping strategies assist prevent soil erosion and maintain existing organic matter levels. The increased ground cover from intercropping protects soil organic matter and significantly lowers erosion rates compared to monoculture systems. Overall, the evidence indicates that intercropping not only boosts organic matter production hence it also supports sustainable agriculture by building healthier soil, nutrient cycling, and biodiversity. Additional studies are necessary to clarify intercropping's potential and ensure its benefits are correctly adapted to different agricultural settings.

2.6.1. COMPARATIVE ANALYSIS OF SOIL ORGANIC MATTER FORMATION UNDER INTERCROPPING AND MONOCROPPING

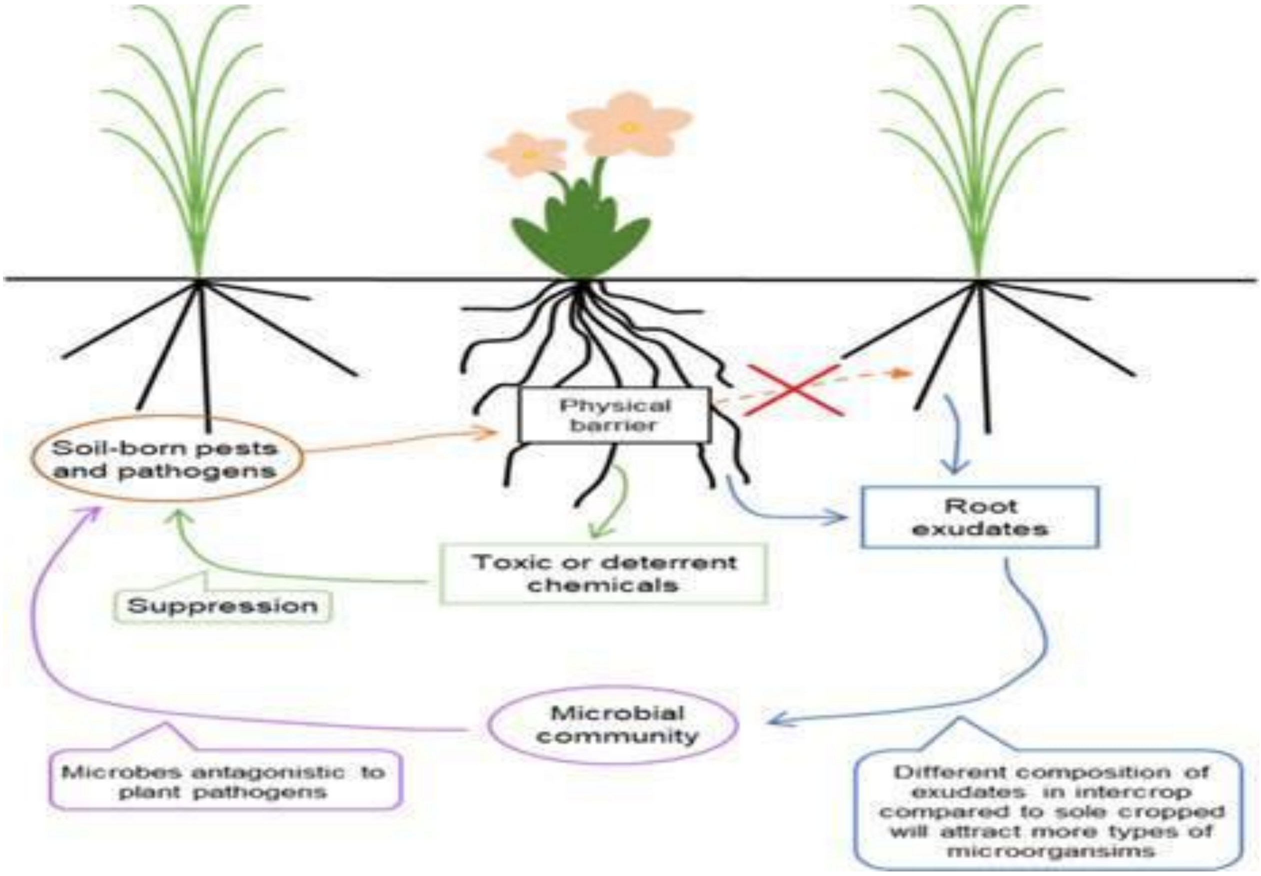

Figure 2.1: Soil organic matter (SOM) formation in intercropping versus monocropping (Homulle *et al*., 2022).

Intercropping is a regenerative agricultural practice that increases soil organic matter, enhances pest regulations and improves overall soil health. As a practical tactic for boosting farm productivity and resilience, it relies on plant diversity, growing multiple species together to interrupt pest life cycles and lower dependence on synthetic pesticides. The greater variety of plants fosters a more resilient agroecosystem, which in turn supports richer soils and often leads to higher yields. In short, intercropping offers an effective, nature-based way to address pest pressure and soil degradation while advancing sustainable agriculture.

2.6. KEY CHALLENGES LIMITING THE CULTIVATION OF INDIGENOUS LEGUMES

According to Abobatta *et al*. (2021), farming indigenous pulses encounters several challenges, including genetic, socio-economic, institutional, and technological barriers. Genetic challenges hinder the ability to crossbreed wild and cultivated species, which render many legumes crops less appealing for agricultural use in various regions. Despite their critical role in improving food security and fostering sustainable agriculture, these constraints prohibit native legumes from fully realizing their potential benefits. This circumstance emphasizes the necessity for focused interventions designed to these constraints and fully realize the potential of indigenous legumes within farming systems.

2.6.1. LIMITED RESEARCH AND DEVELOPMENT AS A CONTRAINT ON INDEGENOUS LEGUME PRODUCTION

Indigenous legumes face significant challenges, particularly when compared to more commonly cultivated varieties like soybeans and chickpeas, primarily due to insufficient research and development efforts. Many indigenous species remain relatively unknown, leading to inadequate breeding programs and suboptimal agronomic practices. An increase of 548.6% in global production of these legumes was observed between 1961-1963 and 2014-2016, driven by a 152.6% expansion in cultivated area (128.37 million hectares) and an 85.9% improvement in productivity. Among the numerous legumes cultivated worldwide, the seven most prominent legumes are common beans, chickpeas, cow peas, ground nuts, lentils, pigeon peas and soybeans (Nigam *et al*., 2021). Furthermore, this lack of knowledge limits the potential for enhancing yield and developing pest and disease resistance, emphasizes the necessity for increased focus on research and development for indigenous legumes.

2.6.2. Genetic Diversity and Conservation: Hindrance to Cultivating Local Legumes

Genetic diversity of native legumes is under threat due to habitat reduction and intensive farming methods. According to Mwanga *et al*. (2023), conventional agricultural practices are depleting genetic resources, reducing the genetic pool accessible for breeding efforts aimed at increasing traits like drought resistance and nutritional value. This loss not only jeopardizes the survival of indigenous species but also limits the potential for developing resilient legume varieties. Additionally, the growing preference for commercially propagated legumes like soybeans further exacerbates this issue, as native legumes struggle to gain attention without proper genetic conservation efforts (Abobatta *et al*., 2021).

2.6.3. Market barriers and weak economic returns endanger the continued cultivation of indigenous legumes

Significant barriers limit consumer uptake and familiarity with native legumes. Ndlovu *et al*. (2022) found that many consumers are unaware of how to prepare these crops or of their nutritional advantages, which makes it difficult for producers to justify growing them amid uncertain demand. Buyers commonly default to widely recognized legumes including cow pea, soybean and Bambara ground nuts. To improve the market prospects for indigenous legumes, targeted efforts to raise consumer awareness and provide education about their culinary uses and health benefits are essential.

2.6.4. Low consumer awareness and restricted acceptance impede the cultivation of legume species

Indigenous legumes often encounter significant challenges in accessing markets, which adversely impacts their profitability. Kamau *et al*. (2023) found that underdeveloped value chains and weak markets discourage farmers from growing these crops. Without adequate market support, farmers are likely to allocate their resources toward cash crops that offer better financial returns, further marginalizing indigenous legumes. While jack bean produced good grain yields, Luz *et al*. (2023) found that seed prices and planting rates were high, the practice proved unprofitable and produced negative returns in both cropping seasons. In contrast, species such as spectabilis and lablab produced better economic results.

Limited market channels and weak commercial viability strongly constrain the expansion of indigenous legumes. Many farmers hesitate to grow them because structured buyers are scarce and returns often fall short of those from conventional cash crops. Without target market development, price incentives, and value-chain investments, these species will likely remain sidelined in favor of more profitable alternatives. It is only by addressing these bottlenecks that the economic viability and cultivation of indigenous legumes can be improved, unlocking their considerable economic potential. Adoption and knowledge of native legumes by consumers are also significant obstacles. According to a study by Ndlovu *et al*. (2022), a few customers are unaware of the culinary applications and nutritional advantages of certain legumes, and producers find it difficult to defend the production of specific commodities because such ignorance may limit demand. Although consumers may find it difficult to replace legumes that are already well-known, like cowpea, soybean, Bambara, and many others, one should make sure that consumer education and awareness are raised to improve market access for local legumes and consequently foster greater appreciation of their worth.

2.6.5. Vulnerability to climate change undermines the continued cultivation of indigenous species

Although many indigenous legumes exhibit resilience to immediate climate conditions, changes in weather patterns can significantly impact their growth, yield, and nutritional quality. Chivenge *et al*. (2023) noted that adapting agricultural practices to these evolving conditions may require additional support and resources for farmers. Like other crops, indigenous legumes are vulnerable to climatic fluctuations, which can adversely affect their yields. For example, Abobatta *et al*. (2021) highlighted that utilizing resistant varieties could help mitigate these challenges; however, the lack of accessible information regarding the development of such cultivars complicates efforts to mitigate these challenges effectively. To ensure sustainability and enhance resilience in indigenous legume production, it is crucial to implement strategies that counteract the adverse effects of climate change.

2.6.6. Competitive interactions between maize and leguminous crops and their complementary impacts on yield and nutrient cycling

When comparing intercropping to monoculture, interspecific competition plays a central role in determining productivity and growth rates. Several indices were calculated including intercropping advantage (IA), competitive ratio (CR), aggressivity (A), relative crowding coefficient (K), and actual yield loss (AYL), have been used to measure the positive competitive impacts across different planting schemes (Yang *et al*., 2016). Although these indices help researchers describe competitive behaviors in intercropping systems and make it easier to compare different studies using the same metrics, they haven't been used to evaluate competition in intercropping setups with different distances between the two species.

According to Martinez *et al*. (2020), jack beans perform two roles in maize intercropping systems: they boost soil fertility by supplying biologically fixed nitrogen whilst increasing crop performance. This increases the agricultural system's overall sustainability and productivity. First, jack beans' slower development enhances biodiversity and environmental processes by allowing other plants to establish themselves naturally. However, when jack beans mature, their growth patterns and root exudates can significantly reduce the density of these volunteer plants, making the environment more regulated and competitive for maize. Figure 2.2 illustrates the competitive dynamics of soybean and maize monocropping versus intercropping.

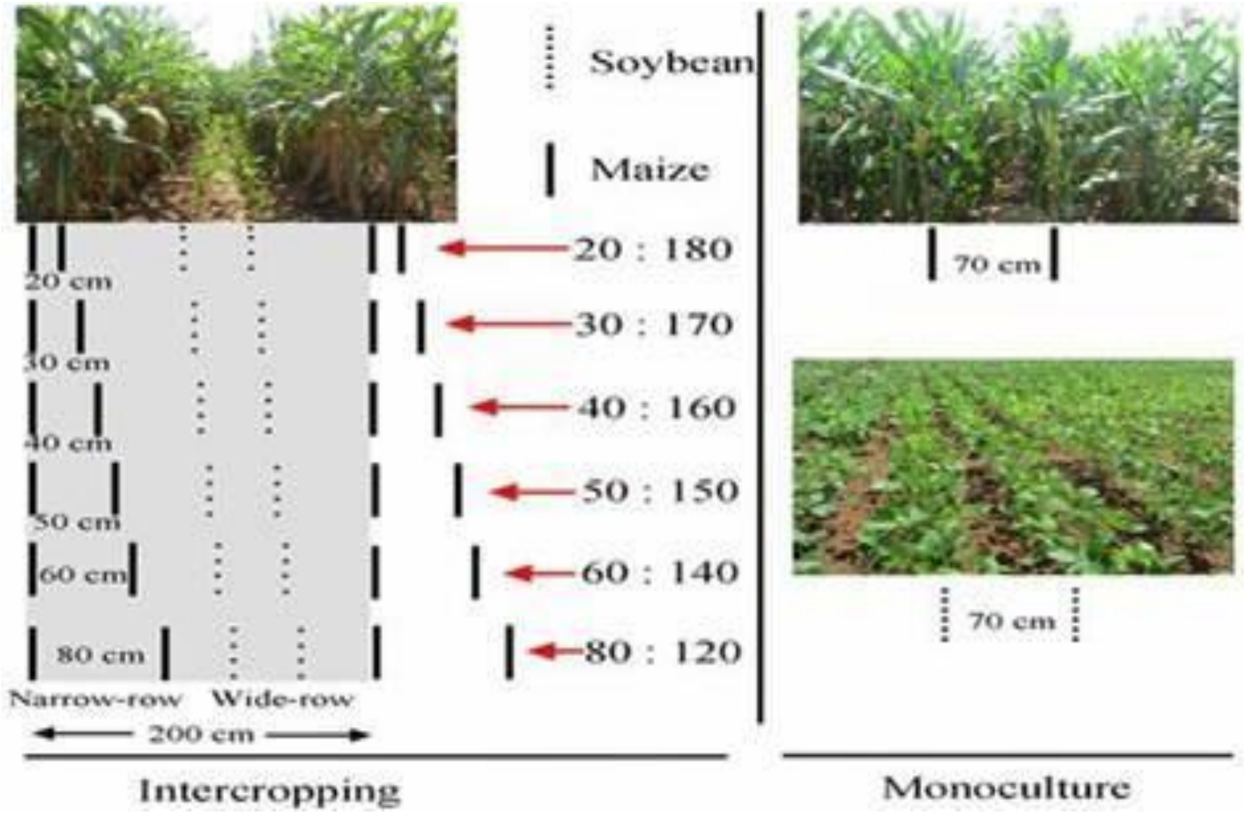

Figure 2.2: Competitive interactions between maize and soybean in monocropping and intercropping systems (Martinez *et al*.,2020**).**

Biotic interaction between jack bean in mixed stands is complex and strongly influences plant performance. Research shows that the shorter jack bean can create a shading and microclimate effect that benefits taller maize plants by improving light use efficiency and suppressing weeds, thereby altering competitive dynamics (Ghosh *et al*., 2021). However, during critical growth stages, jack beans maize interactions can involve competition for critical resources, notably water, and mineral nutrients. Nevertheless, these competitive effects are generally mitigated by the positive interactions fostered within the intercropping system, which enhances overall resource utilization efficiency (Osei *et al*., 2022).

The growth patterns of maize and jack beans complement each other, further optimizing their competitive dynamics. Through biological nitrogen fixation, jack beans add soil nitrogen making it available for uptake by maize. This nitrogen fixation can significantly improve soil fertility, particularly in nutrient-deficient soils (Khan *et al*., 2023). Moreover, the timing of their growth stages plays a vital role; while jack beans may establish later in the growing season, maize grows rapidly in the early stages, effectively utilizing available resources during this period (Badu-Apraku *et al*., 2022).

A complicated yet advantageous competition process that improves overall crop performance and sustainability is demonstrated by the intercropping of maize-jack bean. Complementary growth behaviors of these two species, where jack beans provide shade and raise soil nutrient levels through nitrogen fixation, result in increased yields by enhancing resource use efficiency, despite the possibility of competition for resources like water and fertilizers. Compared to monoculture systems, research shows that intercropping can increase maize yields by 10–30%. Additionally, by adding organic matter from jack bean waste, it enhances soil fertility and biodiversity. Intercropping is a potentially sustainable agricultural strategy because of its synergistic coordination, which increases productivity and maintains nutrient cycling (Ghosh *et al*., 2021).

2.7. INVESTIGATING CHLOROPHYLL CONTENT AND STOMATAL CONDUCTANCE IN INTERCROPPING WITH JACK BEAN

De Souza *et al*. (2024) reported that cover crops significantly influence the chlorophyll content in maize, with the highest levels observed at 14.5 µg cm^2 in maize grown after jack bean. This finding suggests that using jack bean as a ground cover enhances chlorophyll levels in maize leaves, thereby boosting the potential for photosynthesis. Specifically, maize produced after jack bean exhibited, averaged chlorophyll content of 25.6 µg cm^2, which is substantially higher than that of maize grown with other cover crops. This implies a beneficial influence of jack bean on foliar chlorophyll concentration, which likely translates into improved photosynthetic performance in maize.

Significant variation in chlorophyll a/b ratio was observed across phenological stages, with values at the vegetative tasseling stage being lower compared to those recorded at milk grain filling stage. The observed variation indicates maize physiological responses to cover crop treatments are developmentally dependent exhibiting stage specific changes as the crop matures. While jack bean appears to enhance chlorophyll levels, it may not equally improve stomatal conductance. This suggests that although jack bean contributes to increased photosynthesis through enhanced chlorophyll content, it might not optimize water vapor exchange via stomata.

Additionally, the type of cover crop and the growth stage significantly affected gas exchange and stomatal conductance (De Souza *et al*.,2024). In comparison to jack bean, other cover crops exhibited higher stomatal conductance, indicating the favorable microclimate these crops provide for gas exchange processes. Maize yield varied with cover crop treatments, after jack bean attained 15.5 Mg /ha, representing an 8% relative to the 14.3 Mg /ha observed in fallow treatments. This suggests that while jack bean can enhance maize productivity, its effects on physiological factors such as foliar chlorophyll concentration and stomatal conductance are variable (Jafarikouhini *et al*., 2020).

2.8. RELATIONSHIP BETWEEN SEED SIZE AND GERMINATION POTENTIAL

Ambika *et al*. (2014) found a positive results between seed size and early performance, larger seeds germinated more rapidly and generated seedlings with greater root biomass and subsequent yield than smaller seeds. Seed size is a key physical quality factor that influences plant development, seed emergence, and overall crop yield performance. There is a linear relationship between seed size and seed vigor, which means that larger seeds usually result in more vigorous seedlings. Variability in seed size within mixed lots can cause uneven stand density among seedlings, resulting in increased variability in both vigor and growth.

Seed size affects germination success and vigor, with a complex relationship that varies across species and environments. Okonwu *et al*. (2022) found that larger seeds outperform smaller seeds in the field. This higher performance is ascribed to a variety of factors, such as larger nutrient store that fuels growth, a robust root system that enhances water and nutrient uptake, and greater resilience to stresses like drought and competition. Larger seeds typically germinate faster, create more vigorous seedlings, and so result in superior crop establishment and yield results (Dolapo, Adelabu, and Franke, 2023).

Seeds of greater size store more energy, allowing them to germinate quickly and vigorously, which improves seedling establishment (Dolapo, Adelabu, & Franke, 2023). Larger seeds are linked to better seed vigor in many plant species, which is the seed's capacity for rapid germination and growth into healthy seedlings under a variety of environmental circumstances. In agronomic settings like intercropping and competitive cropping systems, where early establishment is essential for optimizing crop production, this energy is especially crucial.

Environmental elements such as water availability and temperature have a substantial impact on seed size and germination. Understanding these dynamics is critical for optimizing planting tactics that improve crop performance in a changing environment. Choosing bigger seeds can help farmers increase seed germination and support healthier plant development in the field.

2.9. YIELD CHARACTERISTICS OF MAIZE IN INTERCROPPING SYSTEMS

In contrast to conventional monoculture methods, Madembo *et al*. (2020) discovered that combining maize with cowpea and jack bean in an intercrop system greatly increases more stable yields. The legume's potential for atmospheric nitrogen fixation, efficiently inhibit weeds, and create ground cover through cowpea are some of the elements that contribute to this greater stability in intercropping systems. Together, these components produce a more stable cropping environment that produces steady yields across several growing seasons. Furthermore, it has been demonstrated that intercropping maize with legumes, especially soybeans, improves nitrogen use efficiency and stability. To maximize resource usage, improve sustainable farming practices, and achieve steady crop yields, the maize-soybean rotation has proven very successful.

According to Raseduzzaman & Jensen (2017), intercropping systems that combine cereals and legumes greatly increase yield stability when compared to monocropping systems. This approach improves food crop diversity, which is crucial for reviving international food security programs, in addition to increasing agricultural yields that are more constant. Conversely, Ladha *et al*. (2022) found that grain legumes were less stable in sole cropping systems, perhaps because of their innate vulnerability to environmental stressors, diseases, and pests. The yields from cereal-legume intercropping were much more stable ($P < 0.001$) than those from pure legume stands. Additionally, compared to cereal-legume intercropping, pure cereal crops showed higher yield stability, suggesting that adding legumes can improve the stability of cereal output (Li *et al*., 2018).

In this context, Begam *et al*. (2024) emphasized the importance of diversifying cereal-based systems by including legumes through intercropping. Increasing the yield of maize on the one hand (and legumes like jack bean, cowpea, and soybean on the other hand) will increase yield stability better than just monoculture farming. This system uses the biological nitrogen fixing ability of legumes plus efficient weed suppression and improve soil cover to provide a more stable cropping environment. Research by Li *et al*. (2018) supports the notion that intercropping maximizes resource use and enhances nitrogen efficiency while promoting agricultural diversity at the farm level that is essential for global food security.

Moreover, advantages of intercropping systems, which demonstrate higher yield stability over time, contrast sharply with the vulnerabilities associated with sole cropping, including increased susceptibility to pests, diseases, and environmental stresses (Zhang and Li, 2021). Dealing with these challenges is vital to uphold sustainable agricultural methods and to attain consistent yields across seasonal variations.

2.10. DISTRIBUTION AND NUTRITIONAL PROFILE OF JACKBEAN

In 2023, Adebayo & Ogunbayo reported that jack bean seeds contain 30.4% protein, 2.6% fat, and 66.0% carbohydrates, and thus they are potential high-protein food. There have been reports of jack beans in Tanzania containing 4.6% water, 29.7% protein, 3.3% fat, 53.9% carbs, and 3.4% ash. This variation in nutrient content also suggests jack bean has enough adaptability to many growing environments. (Chukwuna and Nwokolo, 2020). In Nigeria, Akinmoladun and Afolabi (2021) reported 14.4% water, 34.5% protein, 4.1% fat, 42.1% carbohydrates, 5.9% fiber, and 4.9% ash. This means that jack beans made in Nigeria are more protein-rich than jack beans that are made in other countries.

On a more recent page, Jack Beans from India differ in their nutritional content: namely, 16.7% water, 2.2% reducing sugar, 3.4% total sugar, 0.2% acidity, 10.9% protein, and 12.2% carbs. You have 1.0% fat, 59 g/100 g fiber, and 8.1 g/100 g of vitamins, too, which makes legumes a nutrient-dense food. Different geographical regions differ in their mineral makeup; therefore, jack beans provide excellent sources of protein, vitamins, and other energy supplements. Because jack beans, being nutrient-rich in protein, vitamins, and minerals, are quite flexible, the commodity crop of origin becomes an appealing option for a large segment of the population that needs and benefits from them.

Conclusion

The literature analysis on intercropping maize with jack beans reveals a number of important conclusions that emphasize the benefits and drawbacks of this farming method. Interestingly, intercropping has been associated with higher yields of maize, improved nutritional quality of maize kernels, improved nitrogen fixation that increases soil fertility, and better pest control. According to research, intercropping jack beans with maize can boost yields by 25–30% when compared to monoculture systems. This is mostly because of improved resource usage and less weed competition. Furthermore, adding jack beans to the cropping system has been linked to increased physical quality, as seen by larger kernel sizes, and a greater protein content in maize grains.

Despite these promising outcomes, the review identifies significant barriers to the widespread adoption of jack beans in intercropping systems. One major concern is the limited research on their agronomic practices, pest control strategies, and market viability. The scarcity of studies focused on jack beans, especially when compared to more extensively researched legumes, hinders farmers' willingness to adopt this practice

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CHAPTER 3

INFLUENCE OF MAIZE JACKBEAN INTERCROPPING ON MAIZE GROWTH AND YIELD

3.1. Introduction

As a sustainable agriculture technique, intercropping means cultivating multiple crop species concurrently within a single field for numerous advantages, including enhanced productivity, improved resource use efficiency and increased biodiversity (Zhang *et al.*, 2019). This is because of their complementing growth traits; the combination of maize (*Zea mays* L) and jack bean (*Canavalia ensiformis*) has attracted interest among diverse intercropping systems. While jack beans, a leguminous species, are widely recognized for their capacity in fixing atmospheric nitrogen, enhancing soil fertility and encouraging sustainable agricultural practices, whilst maize is known as a staple food crop that contributes significantly to food security (Ghosh *et al.*, 2020; Mekonnen & Hager, 2023).

Furthermore, an investigation carried out by Ogunleye *et al.* (2020) found that intercropping and cowpea boosted maize grain yield by 30% as opposed to monoculture systems. Similarly, research conducted in India indicated that intercropping maize with pigeon pea can significantly improve growth and yield of two crops, with maize showing a 25% increase in yield due to nitrogen contributions from the pigeon pea (Kumar *et al.*, 2021). Research by Singh (2021) indicated that legumes, such as jack bean, can benefit intercropped cereals by providing essential nutrients and improving soil structure. According to Khan (2022) the relationship between a legume and a stable crop may lead to better resource utilization, as maize can take advantage of the nitrogen fixed by jack bean, while jack bean benefits from the shade provided by the taller maize plants.

Moreover, intercropping has been interlinked with increased pest and disease resistance, as the diversity of plant species can disrupt the life cycles of harmful organisms (Nandwani & Puri, 2020). For instance, a Brazilian study reported that intercropping maize with legumes cut pest and disease incidence by up to 50%, resulting in healthier crops and higher yields (Silva *et al.*, 2022).

3.2. Materials and methods

3.2.1. Description study site

Field experiment was carried out at Makhundu farm based in Nkomazi Region, in the Mpumalanga Province. The farm is located on the Eastern part of the Ehlanzeni district municipality with the latitude of - 25° 61’ 62.7” S and longitude of 31° 68' 24.35" E. The Lowveld region has a tropical climate, with warm subtropical temperatures, annual high temperatures ranging from 26.15º C and annual low temperatures ranging from 13.69 ºC and abundant summer rainfall, between the months of September and March (SA weather service, 2024). Recorded yearly rainfall was **561.4 mm for 2024** (A) and **344 mm for 2025** (B). Annual rainfall distribution during cropping seasons is presented in Figure 3.1 below.

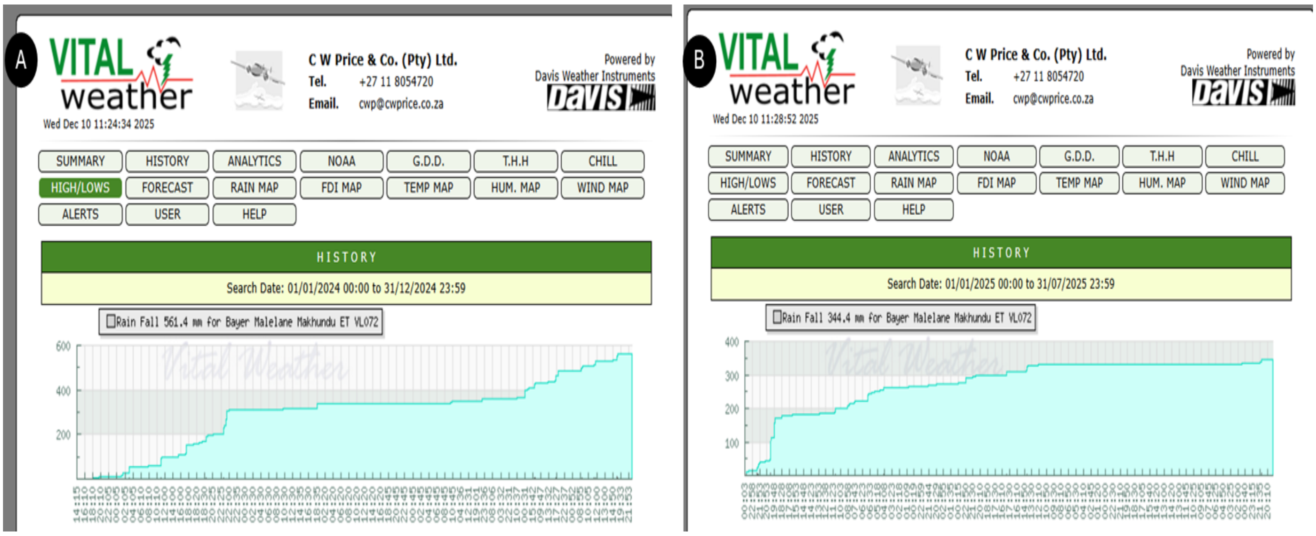

Figure 3.1: Annual rainfall during cropping season.

3.3.2. Experimental design

Research was performed in a Randomized Complete Block Design (RCBD) investigating the effect of intercropping maize with jack bean (Ngwenya *et al*., 2021; Montgomery, 2017). It consisted of three treatments, i.e., sole maize (A), sole jack bean (B) and maize intercropped with jack bean (C), each setup was repeated three times giving nine plots altogether. Plot sizes were 30 m² (5m x 6m), with 1m inter-treatment spacing. Row spacing for the sole maize treatment was set to 0.76 m, and plant spacing was 0.25 m (four-row planter). This gave a rough estimation of 54.333 plants per ha. Sole jack bean plots were hand-planted with an intra-row spacing of 0.25m and inter-row spacing of 0. 90m.This gives a rough estimation of 68.333 plants per ha. Intercropping treatment, two rows of maize alternated with two rows of jack bean, with plants spaced 0.45m within rows. Fifteen plants of each treatment were randomly selected for data collection in order to obtain an accurate assessment of growth and yield. Table 3.2 below shows treatments arrangement.

Table 3.1. Illustrating treatments (RCBD)

Replicates	**Treatments: Monocropping versus Intercropping**		
Replicate 1	**A**	**C**	**B**
Replicate 2	**C**	**B**	**A**
Replicate 3	**B**	**A**	**C**

3.2.1. Planting

First season planting took place in September 2024 and second season in February 2025, aligning with the onset of the rainy season, which is successful for crop cultivation in Mpumalanga (Shongwe *et al.*, 2019). Seeds of jack bean and maize were planted manually with the help of planting sticks. Two seeds per stand were planted so that they could germinate, and after that, thinning was done to have one good plant per stand. Thinning occurred two weeks after emergence to allow for the removal of weak or diseased seedlings. Fertiliser application was guided by soil analysis results from the Agricultural Research Council (ARC) laboratory in Nelspruit. The soil test indicated moderate nitrogen and magnesium levels but deficiencies in phosphorus and potassium. Based on these results, a basal fertiliser mixture of nitrogen, phosphorus, and potassium was applied at planting. For maize, fertiliser was placed in rows at recommended rates of 20 kg N, 40 kg P, and 30 kg K per hectare. Jack bean did not receive nitrogen fertiliser at planting because legumes are capable of fixing atmospheric nitrogen through symbiotic bacteria in their root nodules Maize hybrid cultivar SC 506 was carefully selected for its suitability and adaptability of the climate of Mpumalanga, where hybrid varieties are preferred for their higher yielding potential with increased resistance to abiotic stress and diseases (See figure 3.2.2 for trial plantings A, B & C).

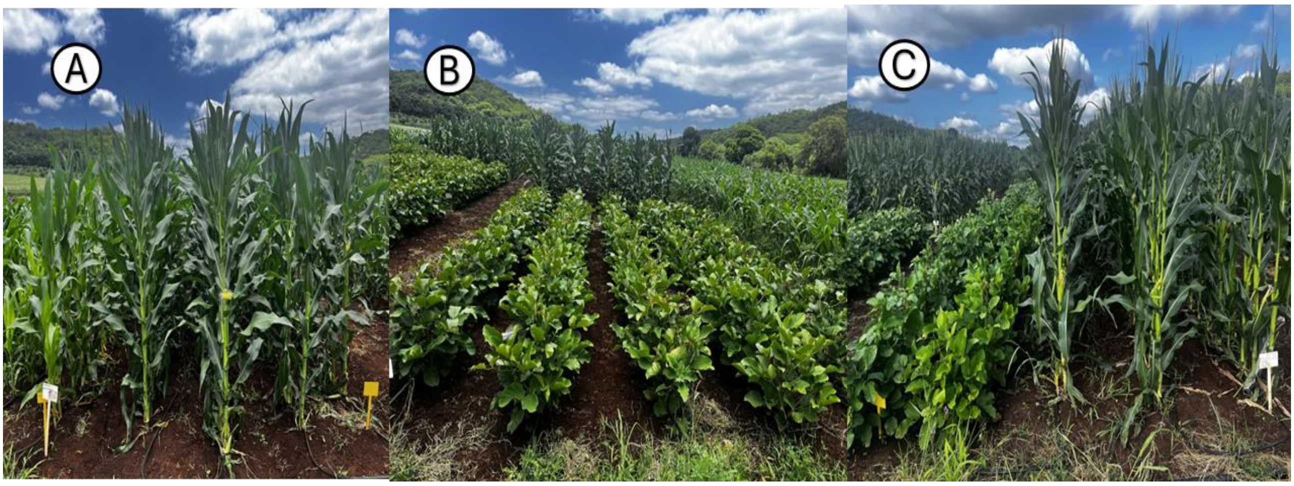

Figure 3.2 Trial planting: Sole maize(A), Sole jack bean(B) & maize-jack bean intercrop(C)

3.3.2. Crop management

Manual weeding was carried out using hand hoes at three and six weeks after planting. (Agegnehu *et al.*, 2017). Diseases and pests were managed through regular scouting. Fall armyworm (*Spodoptera frugiperda*) and stem borers (*Sesamia calamistis*) were the primary pests observed in maize, while aphids and leaf-feeding beetles were checked in jack beans. Through prompt monitoring, insect damage was maintained below economic levels. Since the trial's goal was to test cropping practices rather than pesticide treatments, no chemical pesticides were used unless essential. Additionally, both crops were scouted weekly for common diseases such legume leaf spots, maize leaf blight, and maize streak virus. Affected plants were documented where instances were found, but disease levels stayed low and no chemical management was needed.

3.3.5. Data collection

Throughout the season, growth and physiological data were gathered to assess how well jack beans and maize performed in mono and intercropping systems. Every two weeks, measurements were made to track crop development and evaluate the impact of treatments. (Maitra *et al.,* 2021).

3.3.5.1. Leaf number: was measured and recorded two weeks after emergence, which fully expanded leaves counted for maize and trifoliate leaves for jack bean.

3.3.5.2. Leaf area index was calculated from leaf dimensions and ground area, indicating the canopy's sunlight interception capacity using a method adopted from (Begam *et a.l*,2024)

3.3.5.3. Plant height: Using a technique adopted from (Pierre *et al*., 2022), height measurements were measured from the base stem to the uppermost tip, fifteen specific plants were selected per treatment.

3.3.5.4. Stem diameter: measurements were taken at vegetative growth, at flowering and during grain filling stage, the stem diameter was measured five centimeters above the soil's surface using a venire caliber (Pierre *et al*., 2022).

3.3.5.5. Chlorophyll content index: Using a technique adopted from (Brewer *et al.,* 2022), chlorophyl levels were measured using a SPAD meter on chosen leaves from the uppermost fully expanded leaf at three growth phases.

3.3.5.6. Stomatal conductance: was measured using a porometer to evaluate gas exchange and water use efficiency.

3.3.5.7. Ear growth: was measured using a measuring tape. The ear length and girth from silking to maturity, while jack bean length and number were similarly observed.

3.3.5.8. Roots and nodules: were uprooted and taken to the laboratory for nitrogen analysis using methods adopted from (Begam *et al.*,2024).

3.3.9. Data analysis

Data analysis involved several steps to evaluate growth, yield, quality parameters, and soil mineral nutrients. Data collected from all parameters was tested for normality and it was subjected to the Analysis of Variance (ANOVA) at 5% level of significance using GenStat® 17th edition software from VSN International Ltd., Hertfordshire, UK. Data was analyzed by one-way analysis of variance to test the significance differences between the jack bean cropping systems. Mean separation was performed using Duncan's Multiple Range Test (DMRT).

Additionally, the productivity gains from intercropping versus monocropping were assed using Land Equivalent Ratio (LER). The formula used for LER was

$$LER = \frac{Y_{mi}}{Y_{ms}} + \frac{Y_{ji}}{Y_{js}}$$

where Y_{mi} and Y_{ms} are the yields of maize in intercropping and sole cropping, respectively, and Y_{ji} and Y_{js} are the corresponding yields of jack bean (Nakagawa & Cuthill, 2007).

3.9. Results

3.9.1. Growth Parameters

3.9.1.1. Chlorophyll content index

Chlorophyll content showed significant differences ($p < 0.001$) between intercropped and sole maize systems across both seasons (Fig 3.9.1). Mean SPAD values were higher in intercropped compared to sole maize in Season 1 (53.6 vs. 49.4) and Season 2 (52.8 vs. 48.7). Chlorophyll concentrations increased during early growth, peaked at about week 8, and then declined by week 10. In Season 1, the sole-crop reached its maximum earlier (around week 6), while the intercrop maintained higher chlorophyll levels until roughly week 8. In Season 2, the intercrop generally exhibited higher chlorophyll readings at most sampling dates and retained a greener canopy for a longer period (Fig. 3.9.1).

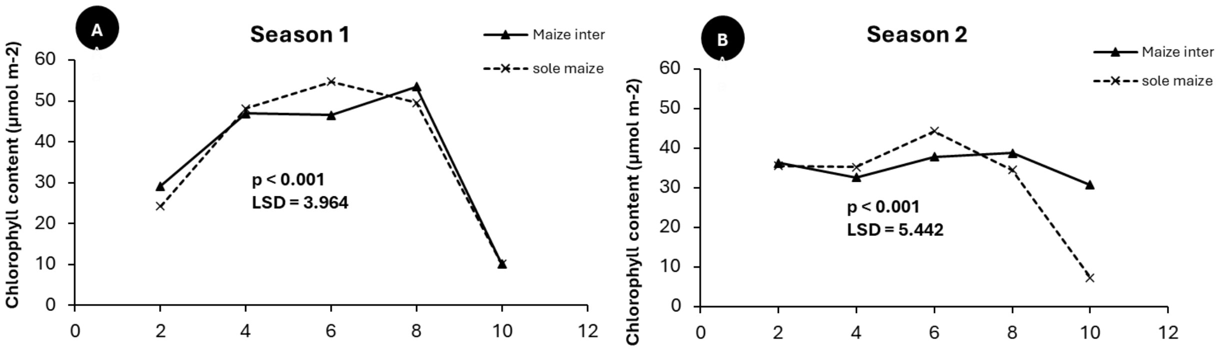

Figure 3.9.1: Comparison of chlorophyll content in intercropped and sole maize across two seasons

3.9.1.2. Ear Growth Length

There was a significant difference between the maize ear growth length ($p < 0.001$) in maize intercropped compared to sole maize for both planting seasons, (Fig 3.9.2). Ear elongation began about four weeks following seedling emergence in both seasons and showed clear dissimilarities between treatments. Season 1, ear length was greater in intercropped maize (25.59cm at week 8, 26.24cm at week 10) than in sole maize (18.39cm and 20.22cm respectively). Treatments differences were highly significant ($p < 0.001$). A similar trend was noted in Season 2, where intercropped maize consistently exhibited longer ear lengths throughout the measurement period ($p < 0.001$).

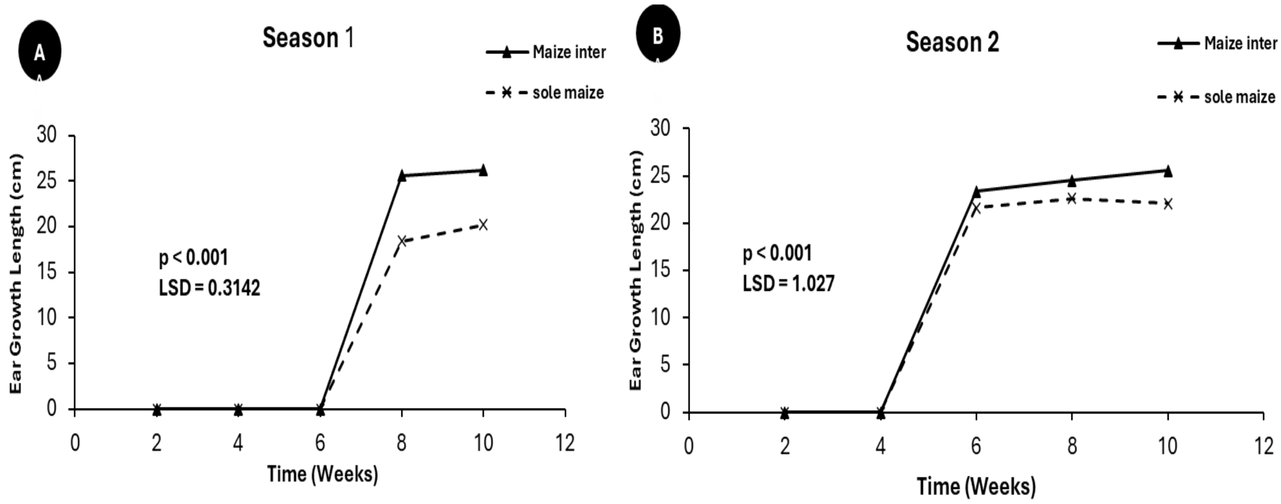

Figure 3.9.2: Ear growth length between intercropped maize and sole maize over two seasons.

3.9.1.3. Leaf Area Index (LAI)

Leaf area index differed significantly between intercropped and sole maize in both seasons ($p < 0.001$) In the first season, the intercrops leaf area grew from 0.16 m^2/m^2, at week 2-0.23 m^2/m by week 8, then fell rapidly to just 0.01 m^2/m at week 10 (see figure 3.9.3). Between week 4 and 8, sole maize canopy was a bit bigger and more stable about 0.25 m^2/m^2, then fell off as plants aged. In the second season , the intercrop hit an early LAI high of 0.92 m^2/m^2 in week 2 while sole maize remained lower and steadier values near through weeks 4–6 and then declined by week 8 (Fig. 3.9.3).These results indicate that intercropping accelerates canopy development in early growth but leads to more rapid canopy loss later, while sole maize sustains moderate leaf area for longer intervals.

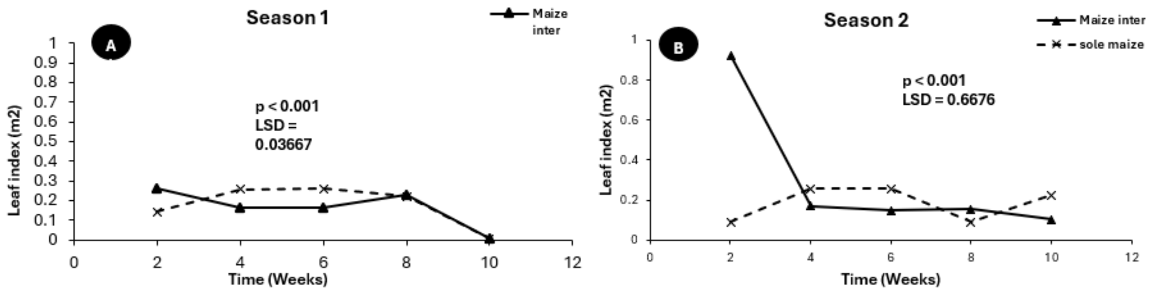

Figure 3.9.3: Leaf area index between intercropped maize and sole maize over two seasons.

3.9.1.4. Plant Height

Cropping system significantly increased maize height for both seasons (p < 0.001). The height increased incrementally with the age of the crop over both seasons (Fig. 3.9.4). By week 10, intercropped maize reached 237.4 cm, while sole maize reached 231.4 cm at the same time in Season 1. In Season 2, however, there are bigger gaps: intercropped maize reached 185.3 cm while sole maize was 161.9 cm (Fig. 3.9.4). Overall, plants reached greater heights in Season 1 than in Season 2, with the intercropping showing a clear tendency to favour tall plants at the last sampling.

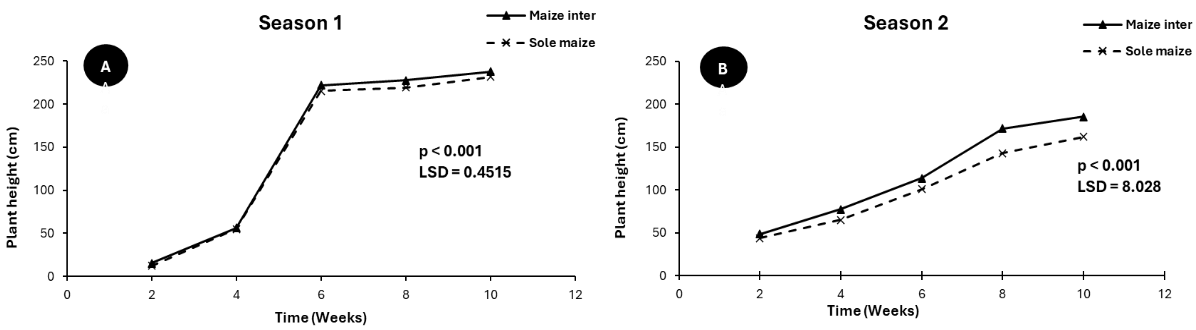

Figure 3.9.4: Plant height between maize intercropped and sole maize over two seasons.

3.9.1.5. Stomatal conductance

Comparisons across the two-planting seasons revealed a highly significant disparity in stomatal conductance between intercropped and sole maize (p<0.001). Season 1 data show conductance rising steeply after week 2, peaking in week 4 and subsequently tapering off through week 10 (Figure 3.9.4). Intercropped maize attained a maximum of 422.6 mmol m^{-2} s^{-1} at week 4, with subsequent values of 400.7 mmol m⁻² s⁻¹ at week 6 and 374.4 mmol m⁻² s⁻¹ at week 8, before falling sharply to 4.4 mmol m⁻² s⁻¹ by week 10. Across both seasons, a comparable trend emerged with maize intercropped sustaining higher average stomatal conductance throughout the season, ranging from approximately 340 to 360 mmol m⁻² s⁻¹, compared to sole maize, which ranged from 300 to 320 mmol m⁻² s⁻¹.

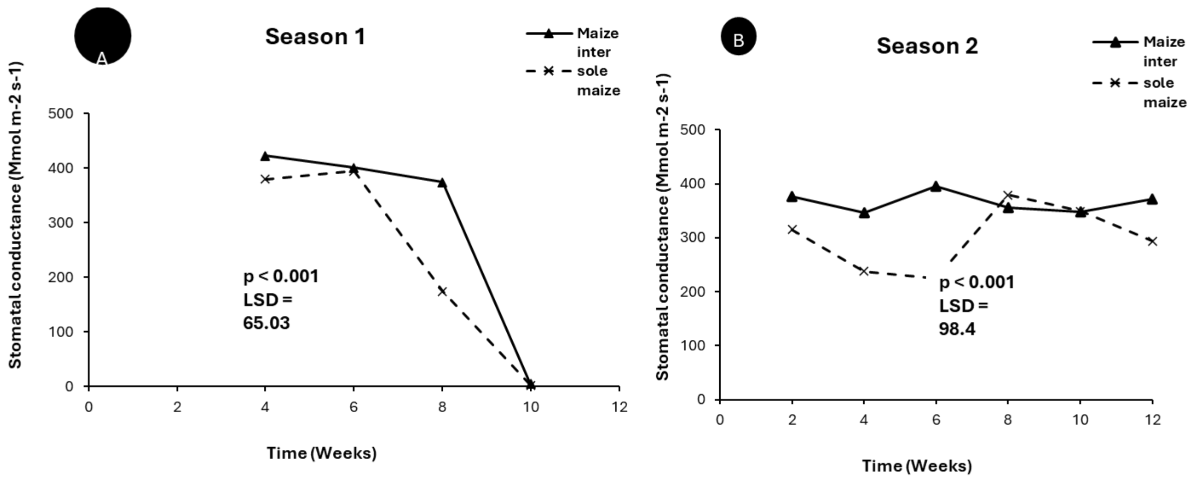

Figure 3.9.5: Stomatal conductance between maize intercropped and sole maize over two seasons.

3.9.1.6. Stem Diameter

Across both seasons, stem diameter differed significantly between intercropped and sole maize ($p < 0.001$) (Table 3.2). In Season 1, intercropped maize increased from 25.16 mm in week 2 to 26.19 mm at maturity, whereas sole maize declined from 23.00 mm to 17.82 mm. Season 2 saw intercropped maize stem width rise from 16.93 mm to 26.60 mm, while sole maize showed a smaller rise from 23.77 mm to 24.50 mm (Table 3.2). Across both seasons, intercropped maize consistently exhibited larger stem diameters, indicating enhanced vegetative vigor and superior phys.

Table 3.2: Mean maize stem diameter (mm) in intercropped versus sole systems

Seasons	Treatments	W2	W10	p-value
S1	Maize- intercrop	25.16	26.19	p<0.001
S1	Sole- maize	23.00	17.82	p<0.001
S2	Maize- intercrop	16.93	26.60	p<0.001
S2	Sole - maize	23.77	24.50	p<0.001

3.9.2. Results on yield Components

3.9.2.1. Cob Length

Across two planting season cob length showed a highly significant difference between intercropped and sole maize ($p < 0.001$) (Figure 3.9.6). In Season 1 cob length averaged 28.09 cm for intercropped maize and 27.30 cm for sole maize. In Season 2, the gap widened with intercropped maize averaging 25.34 cm compared to 13.42 cm for sole maize. The results show that intercropping promoted greater ear and cob development reflecting superior productive performance relative to monoculture.

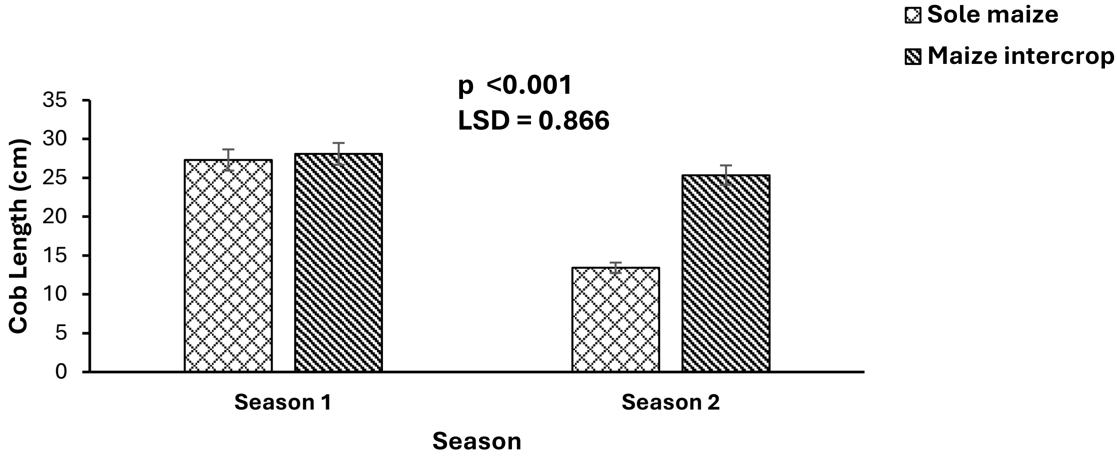

Figure 3.9.6: Comparison of cob length in intercropped versus sole maize across two seasons

3.9.2.2. Cob weight

Cob weight showed a highly significant treatment effect (intercrop vs sole maize) in both seasons ($p < 0.001$; Figure 3.9.7). In Season 1, intercropped maize had a mean cob weight of 0.3478 kg, compared to 0.2722 kg for sole maize. In the 2nd Season, intercropped maize averaged 0.316 kg compared with 0.122 kg in sole maize (Figure 3.9.7). The intercrop thus consistently produced heavier cobs across both seasons, indicating enhanced assimilate partitioning and reproductive performance.

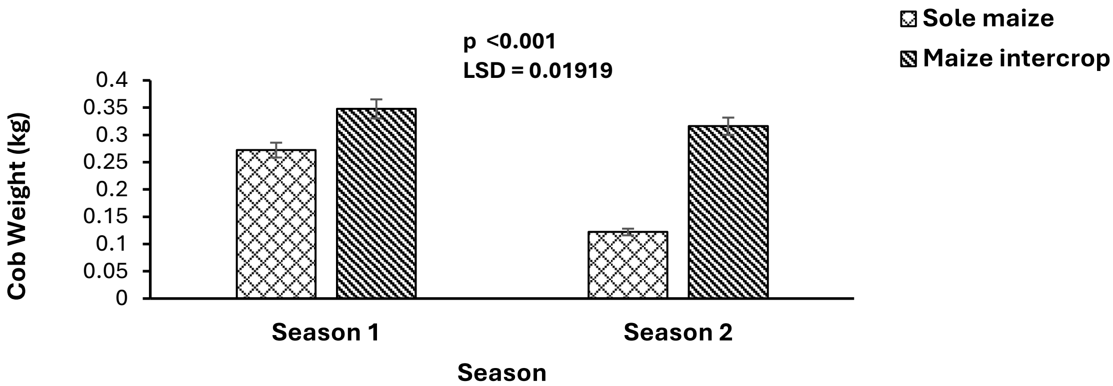

Figure 3.9.7: Cob weight between maize-jack bean intercrop and sole maize over two seasons.

3.9.2.3. Kernel Count per Cob

Number of kernels per cob varied significantly ($p < 0.001$) between intercropped and sole maize in both planting seasons (Figure 3.9.8). In Season 1, intercropped maize averaged 546.7 kernels per cob, compared to 531.5 kernels per cob in sole maize. In Season 2, the difference widened, with intercropped maize yielding the average of 471.1 kernels per cob versus 409 kernels per cob in the sole maize.

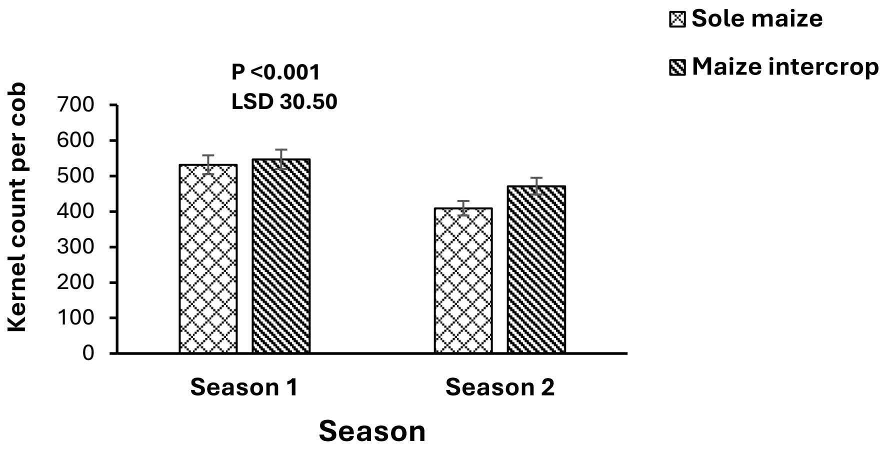

Figure 3.9.8: Kernel count per cob between maize intercropped and sole maize over two seasons.

3.9.2.4. Kernel weight per 100 Seeds

Kernel weight (per 100 seeds) was significant between intercropped and sole maize in both planting seasons ($p < 0.001$; Fig 3.9.9). In Season 1, intercropped maize recorded a mean 100-seed weight of 0.516 kg, compared to 0.300 kg for sole maize. In Season 2, the difference widened further intercropped maize reached 0.9100 kg, while sole maize 0.6933 kg. These results consistently indicate improved nutrient uptake and enhanced grain filling capacity in maize grown with jack bean under the intercropping system.

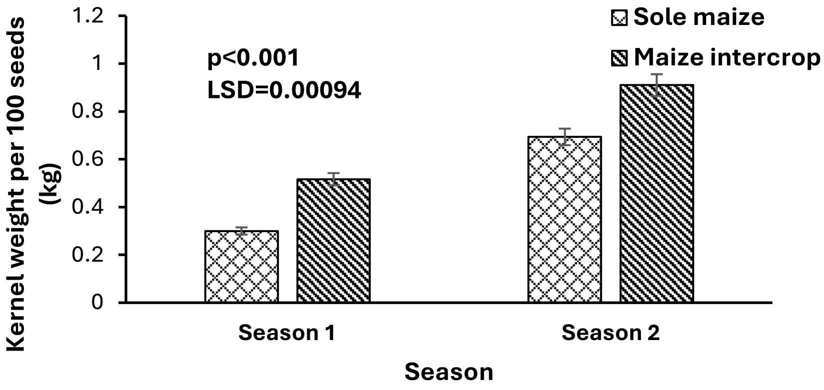

Figure 3.9.9. Comparison of 100-seed kernel weight in intercropped versus sole maize across two seasons.

3.9.2.5. Moisture content (%)

Grain moisture levels were significantly different between maize grown in intercrops and maize grown in monocrop across both seasons ($p < 0.001$; Fig 3.9.11). An average grain moisture of 27.10% was recorded for intercrop maize in season 1 versus 21.95% for sole maize. In the second season, overall moisture contents declined under drier post-harvest conditions, yet the same trend persisted and intercropped retained 14.25% moisture level as opposed to 12.35% for monocrop.

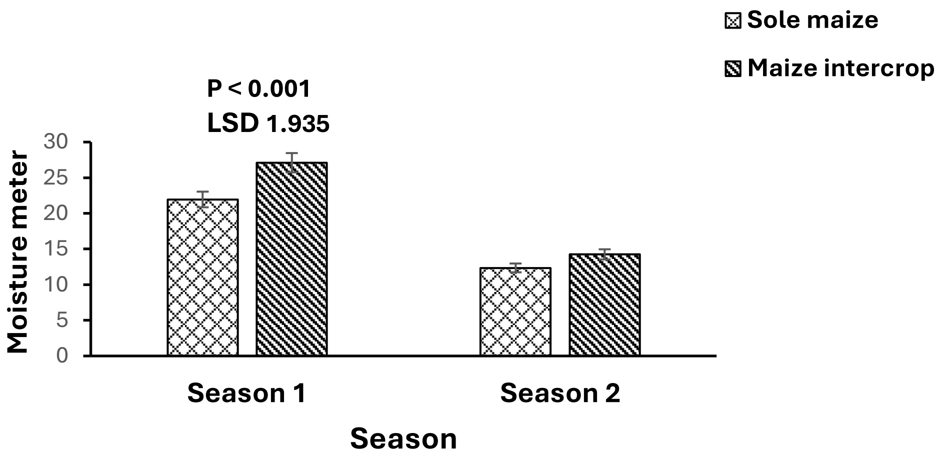

Figure 3.9.10: Grain moisture content between maize intercropped and sole maize over two seasons.

3.9.2.6. Total Grain Weight per Block

Grain yields significantly varied between intercrop and monocrop treatments across planting seasons ($p < 0.001$). Intercropped maize with jack bean averaged 4.435 kg per block in season 1, while sole maize averaged 3.767 kg (Fig 3.9.12). The intercropped persisted in season 2, with mean treatment weight of 0.795 kg for the intercropped plots versus 0.735 kg for the monoculture.

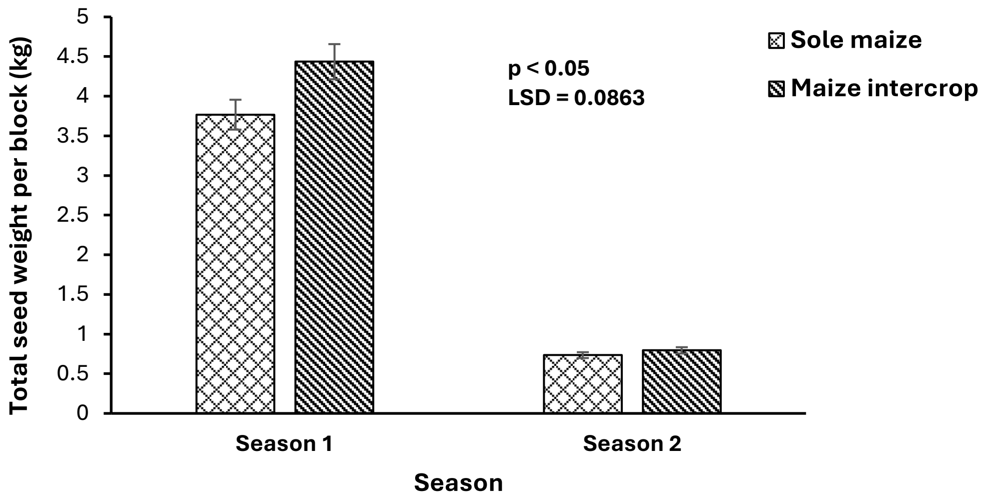

Figure 3.9.11: Total grain weight per treatment between maize intercropped and sole maize over two seasons.

3.9.2.7. Overall Yield Performance and Summary

Across both planting seasons, the overall yield performance of maize was consistently superior under intercropping with jack bean compared to sole maize cultivation. Despite some variation across growth parameters, the combined effect of higher chlorophyll content, greater index leaf area, thicker stems, and enhanced development of kernel translated into higher productivity.

- **Season 1:** Intercropped maize averaged higher values across all yield components, higher cob length (28.09 cm), more kernel (546.7 per cob), 100-seed weight (0.005164 tons/ha) and higher total seed weight (0.004.435 tons /ha).

- **Season 2:** Although yields declined due to drier conditions, intercropped maize still maintained an advantage, with longer cobs (25.34 cm), more kernels (0.00471.1 tons/ha), and higher seed weight (0.00795 tons/ha) (Table 3.3).

The consistent performance advantage of intercropped maize highlights that intercropping improved not only productivity but also yield stability across seasons.

Table 3.3: Maize yield summary across two seasons

Parameters	**S1 (Sole Maize)**	**S1 (Intercrop)**	**S2 (Sole Maize)**	**S2 (Intercrop)**	**Significance (p-value)**
Cob length (cm)	27.30	28.09	13.42	25.34	p<0.001
Cob weight (kg)	0.2722	0.3478	0.122	0.316	p<0.001
Kernel count per cob	531.5	546.7	409	471.1	p<0.001
100-seed weight (kg)	0.300	0.5164	0.6933	0.910	p<0.001
Moisture content (%)	21.95	27.10	12.35	14.25	p<0.001
Total seed weight (kg/block).	3.767	4.435	0.735	0.795	p<0.05

3.4 Discussion

3.4.1. Growth parameters

3.4.1.1. Chlorophyll content

Intercropping advantage aligns biologically with the interactions between legumes and cereals, where the nitrogen fixed by legumes enhances the nitrogen status of leaves and chlorophyll content, thus supporting prolonged effective photosynthesis later in the growing season (Oliveira *et al*., 2022; Lulie *et al*., 2023). Early maximum and subsequent steep decrease observed in sole crops in the current study indicate a quicker onset of senescence, while the later maximum in the intercrop suggests a sustained supply of assimilates during the grain-filling period (Fig 3.9.1) These findings are consistent with reports of a 5% increase in chlorophyll and prolonged maturity in intercrop cereal plus legume, which have strong quantitative evidence (Zheng *et al*., 2022; Johnson and Lee, 2023).

However, these findings are not universally applicable; quantitative synthesis indicates that environmental factors and crop combinations can influence or even negate chlorophyll responses. The positive effects reported in this study are to be made more localized at the subtropical site and season studied and should therefore be considered to reflect that (Pierre et al., 2022; Garcia *et al*., 2021)Several studies have reported similar findings regarding the reduction in chlorophyll content from lower photosynthesis caused by the overshadowing of taller maize plants in intercropped systems compared to monoculture (Wag *et al*., 2017; Peng *et al*., 2021; Oliveira *et al*., 2022). Our research has demonstrated that high chlorophyll content can be achieved through appropriate planting patterns and timing

3.4.1.2. Ear Growth Length

The results demonstrate that maize in intercrop produced longer ears than monocrop maize, confirming that intercropping improved assimilate translocation and ear development (Fig 3.9.2) Longer ears show more reproductive vigor, which might be associated with higher nitrogen availability thanks to the biological fixation of jack bean roots. Legume–cereal systems typically provide nitrogen supply to companion cereals through root exudates and rhizobial activity, enhancing kernel formation and ear elongation (Raza *et al.,* 2019; Zheng *et al.,* 2022). The higher ear length under intercrop also suggests that microclimatic moderation within the canopy, such as reduced temperature stress and better moisture retention supported sustained reproductive growth. These results are consistent with those by Mucheru-Muna *et al.*

(2010) indicated that intercropping of cereal with legume enhanced ear and cob growth through balanced supply sharing and recycling nutrients.

Studies of legume intercropping in subtropical contexts are similar, showing that both increase in ear length due synergistic effects on the fertility of the soil and efficiency of nitrogen (Maitra *et al*., 2021; Chimonyo *et al.,* 2020). According to Ogundeji (2022) monocropping promotes the depletion of soil nutrients resulting in shorter ear length and an unstable yield. Overall, the longer ears observed in maize intercropping show that jack bean maize system enhanced growth reproductively by improving dynamics of nutrients and reducing stress competition, demonstrating the advantage of the intercrop over the monocrop agronomically.

3.4.1.3. Leaf Area Index (LAI)

Leaf area index results show clear differences in canopy behavior between intercropping and monocropping systems. Early in the season, intercropped maize gave increased leaf surface coverage, particularly in Season 2, perhaps reflecting a relatively earlier vegetative response and possibly an increased nitrogen supply from jack bean (Fig 3.9.2). Nevertheless, LAI declined rapidly in the intercrop plots at later stages, suggesting enhanced canopy senescence as grain filling progressed. Sole maize in mid-season held a less unstable canopy structure with slower yet consistent leaf area development. Wang *et al*. (2021) stated that higher LAI early in the intercrop would be beneficial for light interception and early photosynthetic capacity, resulting in higher dry matter content. Early intercropping canopy expansion has similarly been associated with higher available nitrogen and water via synergistic root activity between maize and legumes (Li *et al*., 2019). Conversely, later season declines in intercrop, LAI aligns with reproductive stage resource competition, which can accelerate maturity in dense canopies (Chimonyo *et al.,* 2020).

The results correspond with the findings by Agegnehu *et al.* (2017) who found that cereal legume intercropping provided a potential improvement in early canopy vigor and nitrogen assimilation, but increased leaf senescence rates following reproductive increase. The complementary patterns of early intercrop vigor and late sole-crop persistence in this study suggest differential time profiles that each system optimized use of resource at different growth stages. Overall, LAI observations indicate that maize-jack bean intercropping helps in increasing the early season of photosynthesis potential by rapidly forming a canopy, and sole maize will be able to retain the canopy for longer. This balance drives the intercrop's better overall productivity although the duration of active photosynthesis at the late stage is slightly reduced than during the other crops.

3.4.1.4. Plant Height

Intercropping had a positive influence on maize plant height across both seasons (Fig 3.9.4). Height recorded in intercropped maize implies improved nutrient uptake, particularly nitrogen derived from biological fixation by jack bean (Zheng *et al.,* 2022). Reduced interspecific competition as opposed to intraspecific competition in monocropping is another reason for increased plant height in intercropped maize, which enables maize to make better use of the resources at hand (Agegnehu *et al*., 2008). While the intercrop displayed greater rates of elongation between weeks 4 and 8, which corresponded to the vegetative development phase, the pattern of progressive height rise with crop age matched the typical maize growth trajectory. Better soil fertility and improved moisture conservation made possible by jack bean cover are probably the causes of this increased elongation (Lulie *et al*., 2023).

Maitra *et al*. (2021) observed similar findings stating that cereals intercropped with legumes often grow taller due to complementary nutrient use and canopy light sharing. In a comparable maize–bean system, Chimonyo *et al.* (2020) demonstrated that intercropping led to higher maize height and biomass production, citing nitrogen transfer and efficient radiation use as key mechanisms. Furthermore, small but consistent advantage of intercropped maize in both seasons indicates adaptive growth responses to microclimate adjustment. However, Ghosh *et al.* (2021) reported insignificant results in soybean and maize intercrop where maize height from intercrop was lower than sole crop. The jack bean canopy helps reduce soil evaporation and moderates soil temperature, maintaining favorable conditions for maize root activity. According to Latati *et al.* (2016) legumes contribute to a more balanced soil plant environment, which enhances cereal root growth and water uptake efficiency.

Overall, the results demonstrate that maize height is enhanced under intercropping due to improved nitrogen nutrition, moisture conservation, and reduced intra-species competition. Taller plants under intercropping indicate greater vegetative vigor, which supports increased production potential. The findings show legume intercropping boost sustainability by better resource use and stronger plant structure.

3.4.1.5. Stem Diameter

The results demonstrate that stem diameter was consistently greater in intercropped maize than in sole maize across both growing seasons except for season 2 week 2 (Table 3.2). Thicker stems are a strong indicator of improved nutrient acquisition and mechanical stability, which are directly linked to photosynthetic performance and yield potential (Blessing *et al.,* 2022). The continuous increase in stem girth under intercropping implies that the maize plants benefited from better soil fertility conditions, particularly enhanced nitrogen availability resulting from biological fixation from jack bean.

The reduction in stem thickness in sole maize, especially in Season 1, reflects nutrient depletion and competition stress under monocropping conditions. Such reductions are typical of nutrient-limited systems where soil nitrogen and moisture are insufficient to sustain vegetative growth. According to Latati *et al.* (2016) legumes such as jack bean release nitrogen through root nodulation, improving nitrogen turnover and nutrient uptake in companion crops. The consistent improvement in stem diameter in intercropped maize supports this mechanism. Consistent with results by Li *et al*. (2019), who found that intercropping cereals with legumes enhanced plant vigor and stem girth through moisture conservation and nutrient complementarity. Additionally, intercropped maize plants have stronger stems, which improve lodging resistance and boosts assimilate transfer efficiency during grain filling (Maitra *et al*. 2021). By improving soil structure and organic matter, which promoted root aeration and water uptake, the jack bean probably contributed to these effects (Mtambanengwe and Mapfumo, 2021). According to Pierre *et al*. (2022), when intercropped cowpea (*Vigna unguiculata*), a traditional legume, and solitary maize did not significantly differ from each other. Therefore, the thicker stems observed in intercropped maize demonstrate an agronomic advantage in terms of structural resilience, nutrient transport efficiency, and higher yield stability under field conditions. The results demonstrate that intercropping delivers tangible ecological gains for crop health and productivity, making it a valuable strategy in nutrient stressed subtropical regions.

3.4.1.6. Stomatal Conductance

For each single maize grown in the crop lift system, intercropped corn consistently showed greater and longer stomatal conductance than sole corn. This fact illustrates that under intercropping conditions higher photosynthetic performance results from an enhanced ability to exchange gas with the outside world. The improved temperature-dependence is directly matched by a more efficient photosynthetic process (in contrast between crop and plant). This improvement is ascribed to the better nitrogen availability and the moderated microclimatic conditions resulting from the jack bean component (Maitra *et al*., 2021). Stomatal conductance markedly improved during the early to mid-vegetative period (first, during weeks 2–6) prior to being attenuated by senescence and was consistent with maize physiological evolution. However, consistently high values of intercropped maize indicate a slow age of leafing and improved leaf water status. Extended stomatal activity in this way enhances the incorporation of carbon, supporting further active photosynthesis (Mushagalusa *et al*., 2008). Soil moisture retention increases with stomatal conductance in intercropped systems, resulting from the jack bean canopy and increased root-zone aeration. Legumes enhance soil health indicators which promote water infiltration thus limits evaporation (Latati *et al*., 2016).

Hence, in intercrops maize plants face less physiological stress, and can maintain open stomata for a longer period. Lulie *et al.* (2023), however, found comparable results indicating that legumes enhance soil nitrogen levels and moderate leaf canopy microclimate for stomatal activity in related cereals. Furthermore, Agegnehu *et al*. (2017) found that biological nitrogen fixation and balanced nutrient intake also improved photosynthetic and stomatal conductance of the plants in intercropping systems for legume-cereal crops. Pierre *et al*. (2022), did not find significant changes for stomatal conductance (and water use efficiency), and observed decrease in intercellular carbon rates by 9.74% and 9.15% when comparing maize intercropped with legumes with sole maize treatments. The decrease in conductance in both systems with age indicates normal senescence and diminution of transpiration demand due to fall in leaf chlorophyll levels. However, the reduced decline in intercrop shows that photosynthetic activity is longer, and the soil is supporting grain filling and yield production. This prolonged physiological performance demonstrates the benefits in resource efficiency and crop productivity of intercropping systems in subtropical climates (Pierre *et al*., 2021).

3.4.2. Yield Components and Grain Quality

3.4.2.1. Cob Length

The notable increase in cob length associated with intercropping underscores the benefits of combining jack bean with maize to enhance reproductive growth (Fig 3.9.6). The observed elongation of cobs in both growing seasons can be linked to the improved nitrogen availability resulting from the biological nitrogen fixation conducted by jack bean. This enhanced nitrogen status facilitates critical processes such as ear initiation, kernel development, and grain filling, leading to larger cob sizes (Huang *et al*., 2019).

In the second growing season, the disparity between treatments became particularly pronounced, as the performance of maize grown alone declined under adverse environmental conditions. This indicates that intercropping buffers maize against environmental stresses by conserving soil moisture thus improving nutrient availability. Nitrogen and organic matter contributed by jack bean alleviated nutrient depletion in the maize root zone, thereby supporting ongoing ears to keep growing (Nasar *et al*., 2020).

Consistent with a study by Mucheru-Muna *et al*. (2010) who found increases in grain weight and cob length in maize interplanted with legumes in low-input farming systems. Similarly, Maitra e*t al*. (2021) discovered that because of enhanced nutrient absorption and effective canopy microclimates, maize grown alongside legumes like cowpea and soybean had larger ears. The variation in cob length between seasons further emphasizes the resilience of intercropping systems when faced with subtropical climatic variability. The decrease in cob size for sole maize during the second season indicates nutrient and moisture constraints typical of monocropping practices. In contrast, the intercrop maintained stable cob growth, highlighting benefits of cereal-legume in enriching productive potential under resource limited conditions (Vanlauwe *et al*., 2019).

Economically, longer ears in intercrops suggest more kernels per ear, thus higher yield efficiency. These findings illustrate that maize-jack bean intercropping fosters better reproductive growth and resource utilization, providing practical advantages for smallholder farmers in subtropical regions with limited access to fertilizers.

3.4.2.2. Cob Weight

Measuring cob weight provides a trustworthy estimate of likely grain yield and total crop output. The consistent increase in cob weight of intercropped maize across both growing seasons indicates that integrating jack bean has enhanced nutrient availability and photosynthetic efficiency, leading to greater accumulation in developing cobs (Fig 3.9.7). This improvement can be largely attributed to the nitrogen supplied by the legume, which facilitates sustained kernel filling and increases cob mass (Agegnehu *et al*., 2017). The pronounced difference observed in Season 2, where the performance of sole maize significantly declined, underscores the stabilizing effect of intercropping under stress conditions. Jack bean likely contributed to better soil moisture retention and reduced nutrient loss through leaching, thereby maintaining favorable conditions for grain development.

These conclusions are corroborated by Carton *et al*. (2020), which demonstrates that biological nitrogen fixation and improved phosphorus mobilization in the root zone benefit maize-bean intercropping systems, leading to increased grain mass per cob. Delayed senescence and better canopy balance are further reasons for the higher cob weight in intercropped systems. The results section's increased stomatal conductance and chlorophyll values indicating a stronger photosynthetic capability, which supplies the energy required for efficient cob filling. Consistent with findings by Chimonyo *et al*. (2020) whereby physiological benefits reflect intercropping's role in stabilizing yield and enhancing the translocation efficiency of photosynthetic translocation in semi-arid regions. Furthermore, Hussain *et al*. (2023) observed a drop in cob weight of more than 9% in maize interplanted with legumes as opposed to solitary maize, especially under nitrogen treatments.

From an agronomic perspective, the heavier cobs found in intercropping systems highlight the combined benefits of enhanced soil fertility, moderated microclimates, and efficient nutrient utilization. These improvements not only increase yield per plant but also boost overall productivity per unit area, which is crucial for smallholder farming systems with limited resources.

The findings are consistent with earlier studies that highlight the function of legumes in sustaining grain yields and soil productivity through nitrogen cycling (Vanlauwe *et al*., 2019; Maitra *et al*., 2021). The ecological principle of complementarity, which minimizes direct competition and maximizes yield results through different root structures and nutrient acquisition mechanisms, is best shown by the maize-jack bean system.

3.4.2.3. Kernel Count per Cob

Maize -jack bean intercrop significantly improved number of kernels per cob, showing that stable crop and legume combination improved production potential and reproductive success. The increased number of kernels reflects improved nutrient uptake, enhanced photosynthetic efficiency, and prolonged reproductive activity under intercropping conditions. These effects are closely related to the nitrogen that jack beans contribute to maize fertility and grain development through biological fixation and root exudation (Agegnehu *et al.,*2017). Higher kernel count in intercropped maize also suggests improved pollination and fertilization efficiency. Greater plant vigor and higher chlorophyll levels extend the period of silk receptivity and pollen viability, supporting kernel set and reducing abortion rates (Maitra *et al.,*2021). In contrast, the decline in kernel number in sole maize likely resulted from nutrient limitations and early senescence, common under monocropping systems with reduced soil fertility.

In Season 2, when environmental stress conditions, specifically decreased rainfall, limited nutrient availability, the benefit of intercropping was especially noticeable. In comparison to monocrop conditions, maize was able to sustain reproductive activity for a longer period to the legume component's anticipated improvements in soil nutrient mobility and water use efficiency. These mechanisms align with the findings of Latati *et al.* (2016) who demonstrated that legume intercropping enhances reproductive stability and grain filling in cereals through complementary nutrient dynamics. Chimonyo *et al*. (2020) reported similar outcomes, noting that intercropping increased nitrogen uptake and canopy light usage efficiency in maize–cowpea systems, improving kernel number and ear size. The results similarly support the findings of Lulie *et al*. (2023), who found that better nutrient remobilization and delayed senescence allowed cereals interplanted with legumes to maintain larger kernel counts. Hussain *et al*. (2023) observed dissimilar results where there was recordable 12% and 13% decrease in kernel count and grain weight, this was attributed to a decrease in photosynthesis and chlorophyll pigmentation during growth period.

Overall, the increased kernel count in intercropped maize demonstrates that the intercrop system enhances grain filling and resource usage efficiency, guaranteeing more consistent yields even in the face of fluctuating environmental conditions. Because of this, intercropping is beneficial to smallholder systems in subtropical areas both agronomically and environmentally.

3.4.2.4. Kernel Weight per 100 Seeds

The results confirm the heavier grain with maize intercropped with jack bean when compared to those grown monoculturally. Kernel weight reflects the last phase of grain filling and assimilates translocation, both of which are strongly influenced by nutrient supply and photosynthetic activity. The extra kernel weight observed during intercropping indicates that maize nutrients were enhanced by jack bean's nitrogen fixation, thereby contributing to greater assimilate accumulation in maize during kernel formation (Agegnehu *et al*., 2017). Intercropped maize was probably improved by enhanced soil fertility, especially increased nitrogen and phosphorus availability, and moderated microclimatic conditions within the intercrop canopy. Increased chlorophyll levels and stomatal conductance suggest an extended photosynthetic period, which is beneficial for more efficient carbon sequestration and kernel filling. These physiological benefits make grain denser and have higher mass. These results corroborate the findings of Cheriere *et al*. (2020) who observed the improvement of kernel mass as well as grain quality, as a product of better root interaction and resource sharing were achieved through legume–cereal intercropping systems. Similarly, Maitra *et al.* (2021) reported that maize intercropped with legumes produced heavier kernels due to the enhanced nitrogen remobilization of nutrients by legumes. Research by Carton *et al.* (2020) elaborated that in certain cases, in intercropping, nutrient competition could be involved with lower kernel weight.

The same trend between the two seasons also underscores the resilience of intercropping systems. While Season 2 experienced more variable conditions, intercropped maize still maintained its kernel weight advantage, confirming that the legume component mitigates stress impacts by sustaining soil moisture and nutrient supply (Chimonyo *et al.,* 2020). In agronomic terms, higher kernel weight directly improves yield efficiency and grain quality, which are key measures of overall production output. Therefore, it excels in both overall output and the inherent quality of harvested grains.

3.4.2.5. Moisture Content

The higher grain moisture content in intercropped maize may indicate that intercropping affected physiological maturity and the microclimatic conditions around the maize canopy. Increased canopy cover in intercrop plots decreased direct evaporation, thereby increasing relative humidity and, in turn, the drying time of grains. This outcome concurs with Mucheru-Muna *et al.* (2010), who found that cereal–legume systems improve canopy structure, increase soil moisture retention, and delay leaf maturity. Maize intercrop, with a correspondingly higher moisture content, a longer grain-filling period is also observed, which generally promotes kernel growth and grain mass. The nitrogen supplied by the jack bean likely contributed to the continued photosynthetic activity, thereby delaying physiological maturity. It was also observed by Latati *et al.* (2016) who found that biological nitrogen fixation in legume–cereal intercrops can also prolong reproductive activity and enhance grain quality.

Higher moisture content during harvest is linked to healthier and more full grain filling, although it may necessitate longer drying durations before storage. According to Agegnehu *et al*. (2017), nitrogen-enriched intercropping methods also encourage delayed senescence, which prolongs metabolic activity and produces grains with higher water content at harvest. Seasonal comparison shows that intercropped maize maintained to exhibit higher moisture retention than sole maize, despite the overall moisture declining in the second season owing to drier weather. This resilience highlights the intercrop's capacity to maintain plant water status and stabilize the microclimate even in unpredictable circumstances. Research outcomes are consistent with those of Chimonyo *et al*. (2020), who discovered that intercrops based on legumes reduce the effects of drought by distributing complementing roots and capturing water. This pattern illustrates the two advantages of intercropping in agronomic methods. Although there may be a delay in physiological maturity, improved yield and kernel filling lead to more consistent grain quality. Thus, in subtropical environments, the maize–jack bean system improves both yield and adaptability.

3.4.2.6. Total Seed Weight per Block

Consistent with expectations in season 2, maize grown in an intercrop produced greater seed mass than maize in monocrop, thus indicating total productivity per unit area was greater in maize–jack bean intercrop. This yield improvement reflects the combined effects of improved physiological productivity, larger kernel number, and heavier kernel weight under intercrop conditions (Sections 4.7.3 and 4.7.4). Increase in total seed weight is attributed to an increase in nutrient efficiency and a favorable microenvironment in intercrop plots. The nitrogen-fixing capacity of the jack bean presumably made the soil more accessible to additional nitrogen input, allowing maize to last longer in grain filling. This result is consistent with those reported by Li et al. (2023) that maize-bean intercropping promoted improved nitrogen usage and increased seed mass per unit area in nutrient poor soils.

A small decrease in yield observed in Season 2 was linked to unfavorable weather, particularly the lack of rainfall. Following the findings of Hong *et al*. (2019), this result shows the lowest seed weight in intercrop compared to monocrop, due to inadequate nitrogen availability in the intercrop compared to rhizobia-inoculated blocks. Legwaila *et al*. (2021) found that per-plant grain and dry-matter yields were lower in cowpea–maize intercropping systems than in sole-crop systems. Still, intercropped maize yielded slightly more co-cropped crops when tested, suggesting that intercropping gives more stability and resilience than to stress. Similar resilience was observed by authors who proved that cereal-legume systems reduce loss of yield in dry season by saving moisture in the soil and improving nutrient uptake in the cereal legume system (Mucheru-Muna *et al.* (2010) and Chimonyo *et al*. (2020))

The interaction between maize and jack bean seems to help the use of water, light and nutrients, which is also known as a land productivity enhancement. As supported by Maitra et al. (2021) complementary root architecture with canopy structure can result in improved resource partitioning, less competition and long-term total yields. In agronomic theory, greater seed weight in each block, greater the economic return and yield of staple food. The results concur with the land equivalent ratio (LER > 1), signifying that the intercrop produces more per unit land than sole crops. The maize–jack bean intercropping thus represents one such sustainable intensification strategy, which is especially important for smallholder farmers in subtropical regions where synthetic inputs are largely absent (Vanlauwe et al.,2019).

3.4.3. Land Equivalent Ratio (LER) Calculations

The Land Equivalent Ratio **(**LER) quantifies the efficiency of land utilization in intercropping relative to sole cropping (Kermah *et al.*, 2017; Fu *et al.* 2023). The LER is calculated as per the equation below:

$LER=YimYsm+YijYsj$

where: **Yim** = yield of intercropped maize, Ysm = yield of sole maize, **Yij** = yield of intercropped jack and Ysj = yield of sole jack bean.

In this study, Season 1, 2024 LER recorded was 1.8416 and season 2, LER recorded was 1.4550.

3.4.4. Overall Yield Performance and Summary

The results provide clear evidence of the superiority of intercropping maize and jack beans with respect to monocrop yield parameters. The resource efficiency of the intercropping system is demonstrated by the continuous increase in cob dimensions, kernel numbers, and total grain mass. This enhancement can be ascribed to better soil nutrient cycling, moderate microclimatic conditions in mixed canopies, and nitrogen fixation by jack beans (Agegnehu et al., 2017; Latati *et al.*, 2016). A yield benefit even in unfavorable Season 2 conditions shows the robustness of intercropping systems. With the legume component, soil nutrient depletion and moisture stress effects were reduced, thus keeping productivity stable. Mucheru-Muna et al., (2010) and Chimonyo et al., (2020) demonstrated the same, that maize–legume intercrops achieved stable yields, despite varying rainfall, because of improved soil moisture retention and greater nutrient use efficiency. The physiological improvements described in section 4.1-

4.6 increased chlorophyll, higher stomatal conductance and thicker stems were associated with an assimilate supply during reproductive stages.

This synergetic effect between physiological vigor and soil fertility improvements is evidence that yield enhancement has been systematic, and the impact has not been accidental (biological and environmental) (Maitra et al., 2021). It is, furthermore, indicated by intercropped maize yielding better which follows land equivalent ratio (LER) concept whose productivity per unit area of land is more than sole cropping systems. In comparable cereal-legume systems, the value of LER observed tends to exceed 1.2 indicating land use efficiency (Chunjie et al., 2023). Such systems improve yield and sustainability, key parameters for smallholder agriculture in subtropical regions where land and inputs are limited.

In summary, maize intercropped with jack bean proved superior performance in yield quantity and quality. The intercrop enhanced resource use efficiency, stabilized output across seasons, and contributed to improved soil fertility, validating it as a sustainable agronomic strategy for productivity enhancement in subtropical environments.

3.5. Conclusion

The advantages and methods of intercropping maize with jack beans have been thoroughly covered in this chapter, emphasizing how it can improve agricultural output and sustainability. Combining these two crops maximizes resource usage through complimentary growth features while also improving yield components including cob length, weight, and kernel count. The results show that jack beans' capacity to fix nitrogen greatly enhances soil fertility, thus promotes growth and development of maize. Furthermore, compared to sole maize farming, the intercropped system showed resilience in a variety of environmental factors, sustaining higher yields and superior physiological performance. For smallholder farmers dealing with issues like resource scarcity and climatic variability, this resilience is highly important.

The results also demonstrate the ecological advantages of intercropping, including improved soil health and resistance to illnesses and pests. The observed increases in chlorophyll content, stomatal conductance, and overall plant vigor provide more evidence that intercropping systems can lead to more efficient photosynthesis and nutrient utilization. By demonstrating a land equivalent ratio greater than one, this study suggests that intercropping maize with jack beans is both an effective approach to increase production and a sustainable strategy to manage agricultural systems in subtropical climates. This chapter emphasizes the need for continued study and the use of intercropping techniques to enhance food security and promote sustainable agricultural growth.

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CHAPTER 4

THE EFFECT OF INTERCROPPING ON MAIZE AND JACK BEAN QUALITY AND SOIL MINERAL NUTRIENTS

4.1. Introduction

Intercropping offers a viable way to improve food security while fostering ecological balance and sustainability in agricultural systems as the world's food demand grows, population increases and issues like soil degradation and climate change worsen (Adekiya *et al.*, 2021). Recent research has shown that intercropping jack beans (*Canavalia ensiformis*) with maize (*Zea mays* L) improves the soil's mineral nutrient content and maize quality. According to Adekiya *et al.* (2021), protein content of maize grains increased from 7% in sole maize between 8.5% and 10.2% when jack beans were intercropped. The jack bean's capacity to fix nitrogen, which increases the amount of nitrogen available in the soil, is mostly responsible for this enhancement. Furthermore, study by Zhang *et al.* (2022) discovered that intercropping legumes and maize increased quality by 15% on average, indicating increased resource efficiency due to the two species' complementary development patterns. Additionally, intercropping increases soil nutrient conservation and retention by preventing soil erosion.

Intercropping has also proven to be advantageous in terms of soil mineral nutrients. According to Ofori and Stern (2020) intercropped plots produced an average increase of 30 kg N/ha over sole maize plots, indicating a considerable rise in soil nitrogen levels. Performance of maize production depends on increased nitrogen availability. Additionally, Mureithi *et al.* (2023) found that intercropping increased soil potassium and phosphorus levels, with intercropped plots showing a 25% increase in phosphorus content. These advantages are facilitated by the jack bean's deeper root structure, which helps mobilize nutrients from the soil, and these results highlight the benefits of intercropping as a sustainable farming method that improves soil health and crop quality.

4.2. Methodology

4.2.1. Study area

The experiment was performed according to methods outlined in chapter 3, under same conditions (in September 2024 and February 2025).

4.2.2. Aim of the study

This study aims to evaluate the performance of maize when intercropped with jack bean under subtropical conditions in Mpumalanga province, South Africa, focusing on the effects on maize growth, yield, quality, soil fertility in comparison to monocropped maize.

4.2.3. Experimental design

The experimental design is similar to the previously described in (Chapter 3).

4.2.4. Data collection methods

4.2.4.1. Yield quality attributes

After 120 days of growth cycle, maize cobs were harvested, leaving behind jack beans as they mature later (180 days) than maize. Quality parameters for maize crops such as protein content, starch, moisture content and fiber were analyzed at ARC laboratory in Pretoria.

4.2.4.2. Plant density & Kernel count was calculated by counting all plants in each plot and the stand density influences yield potential. Maize kernel counts were done at harvest involving shelling of cobs and weighing grains, whilst jack bean seed count was recorded by opening pods (Tandzi & Mutengwa, 2019).

4.2.4.3. Moisture content at harvest grain moisture was determined using a grain moisture meter, with weights adjusted to a uniform moisture level to ensure accurate yield comparisons.

4.2.4.4. Protein content dried kernels from each treatment were taken to the laboratory for protein analysis, using an official method of analysis by (Ekanem *et al.*, 2022).

4.2.4.5. Crude fiber samples were weighed and air dried at the laboratory, adopting method from (Ekanem *et al.*, 2022).

4.2.4.6. Carbohydrates contents were determined by subtracting the values of fiber, protein and fat from the total dry matter, using and adopted method from (Ekanem *et al.*, 2022)

4.2.4.7. Soil mineral nutrients soil samples were taken for analysis before and after planting, then analyzed using a standard laboratory technique following a method by Begam *et al*. (2024).

4.2.4.8. Fat content dried separate kernels from the two cropping systems were taken into the laboratory for fat analysis using the official methods of analysis (Ekanem *et al*, 2022).

4.2.4.9. Yield and quality assessment

Grain output per unit area was used to quantify yield, while laboratory analysis of the harvested kernels and seeds was used to evaluate quality. The formula outlined by Tandzi and Mutengwa (2019) was used to accurately estimate grain yield, where grain yield per ha was used to estimate the yield.

(GY (t/ha) = (Grain weight X10 X (100 -MC)/(100 -Adjusted MC)/(Plot Area),

Grain weight, plot size, and adjusted moisture content were used to calculate plot area in m2 per hectare, moisture content (MC) in percentage (%), and grain weight in kg.

4.2.5. Data analysis

VSN International's GenStat® 17th edition software was used to conduct statistical analysis. At the 5% level of significance, treatment methods were compared. Duncan's Multiple Range Test (DMRT) was used to do post-hoc multiple comparison tests. The relationship between nutritional analysis and soil nutrient levels was also evaluated using correlation analysis. Details on the relationship between factors like protein, carbs, fiber, ash, fat, and soil mineral nutrients were derived from the correlation. These correlations support practice suggestions and demonstrate therapeutic effects (Maitra *et al*., 2021).

4.3. RESULTS

4.3.1. Moisture content

No significant difference in moisture content was observed between intercrop and sole maize in either season ($p > 0.05$) (Fig 4.1). In Season 1, intercropped maize had an average moisture content of 10.56%, compared with 10.51% in sole maize, this difference was statistically insignificant. In Season 2, the overall moisture content was lower, but the trend persisted: i.e. intercropped maize retained 10.96% moisture compared to 10.81% for sole maize.

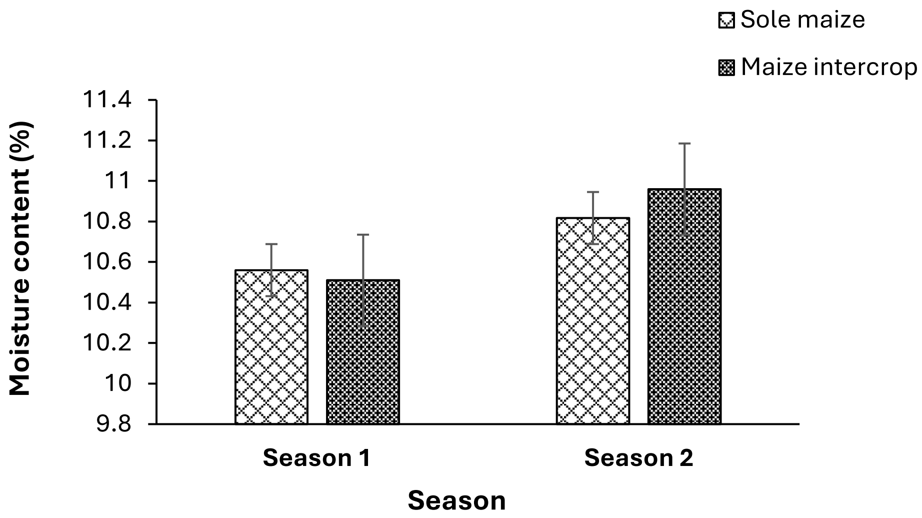

Figure 4.1: Moisture content per treatment between maize intercropped and sole maize over two seasons.

4.3.2. Protein content

Protein levels were significantly higher in intercropped maize than in sole maize in both planting seasons ($p<0.001$). In Season 1, intercropped maize averaged10.88% protein versus 9.61% in sole maize. In Season 2, intercropped maize averaged 8.12% compared with 7.87% for sole maize.

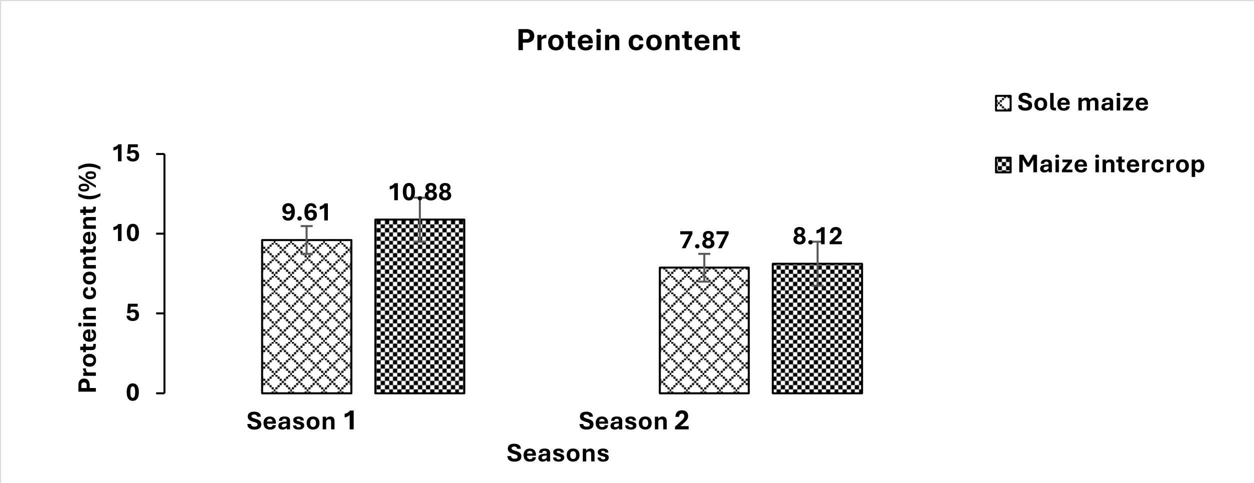

Figure 4.2: Protein content per treatment between maize intercropped and sole maize over two seasons.

4.3.3. Other quality parameters

Analysis of maize nutritional quality for both seasons showed insignificance ($p > 0.05$) on several parameters amongst the two cropping systems. With carbohydrates values of 72.90% for sole maize and 73.50% for intercropped maize in Season 1 and 72.75% for sole maize compared to 74.28% for intercropped maize in Season 2, there was no significant variation in the carbohydrate content (Table 4.1

Crude fiber content similarly showed no significance ($p > 0.05$), with intercropped maize recording 4.65% in both seasons and sole maize recording 5.40% in Season 1 and 3.70% in Season 2. This shows that intercropping techniques do not significantly change maize fiber content, indicating that both systems offer comparable levels of dietary fiber, which are crucial for digestive health.

With values ranging from 89.183% to 89.527% across treatments and seasons and a p-value of 0.712, the dry matter percentage, which represents the total biomass and nutrient density of the maize, also did not exhibit any significant variations ($p > 0.05$) between mono- and maize jack bean intercrop (Table 4.1). This suggests that the total yield quality in terms of biomass is constant across both cropping systems since the intercropping of maize with jack beans has insignificant effect on the dry matter content.

Having a p-value of 0.002, the ash content, which is a measure of the mineral composition and overall nutritional quality, showed that there was significant difference ($p < 0.05$) between mono- and intercropped maize. The ash percentage of intercropped maize was marginally lower at 1.41% in Season 1 compared to 1.50% for sole maize. In Season 2, the ash level of the intercropped maize was 1.47%, while that of the sole maize was significantly higher at 4.00% (Table 4.1). This notable fluctuation implies that intercropping may affect the mineral content of maize, but more research is necessary to comprehend the underlying mechanisms.

Significant difference ($p < 0.05$) was also recorded in the fat content, where sole maize showed the average of 5.43% in Season 1 and 4.56% in Season 2, while intercropped maize showed lower values of 3.70% and 5.16%, respectively, with a p-value of 0.021 (Table 4.1).This suggests that intercropping had an impact on maize fat levels, possibly as a result of the competitive interactions between jack beans and maize that change metabolic processes and nutrient allocation.

Table 4.1: Comparative analysis of maize grain quality over two seasons.

Parameter	**S1 (Sole Maize)**	**S1 (Intercrop)**	**S2 (Sole Maize)**	**S2 (Intercrop)**	**Significance (p-value)**
Carbohydrates (%).	**A** 72.90	**C** 73.50	**A** 72.75	**C** 74.28	0.50
Crude fiber (%).	**A** 5.40	**C** 4.65	**A** 3.70	**C** 4.65	0.39
Ash (%).	**A** 1.50	**C** 1.41	**A** 4.00	**C** 1.47	0.002
Dry matter (%).	**A** 89.43	**C** 89.53	**A** 89.18	**C** 89.21	0.71
Fat (%).	**A**5.43	**C** 3.70	**A** 4.56	**C** 5.16	0.021

Soil nutrient analysis: Baseline soil properties

Baseline soil properties differed markedly by site and season. Soils were slightly to moderately acidic, with KCl pH values ranging from 5.53 to 5.76. Total nitrogen showed a very wide span (2.46–59.10 mg kg^{-1}), while plant-available phosphorus ranged from 5.72 to 125 mg kg^{-1}. Exchangeable potassium values varied between 1.56 and 96 mg kg^{-1}, and calcium and magnesium concentrations determined by ammonium-acetate extraction indicated site-specific cation supplies and imbalanced cation ratios in some plots. This heterogeneity in baseline fertility and cation status is likely to influence crop responses to management (including intercropping), so it should be factored into experimental design, analysis (e.g., blocking or covariate adjustment), and site-specific recommendations.

Table 4.2: Baseline soil characteristics by site and season

Units: pH in KCl; N, P, K in mg kg^{-1}; Ca%, Mg% by ammonium acetate extraction.

Sample ID	Seasons	pH (KCl)	N	P	K	Ca% (AmAc)	Mg% (AmAc)
M4	1	5.76	10.00	119.00	78.00	62.18	29.81
M4	1	5.53	20.52	125.00	96.00	66.19	42.11
M15	2	5.72	2.46	5.72	1.56	73.60	240.00
M15	2	5.57	59.10	31.64	6.40	28.70	1161.00

Table 4.3: Derived cation ratios and charge metrics

Derived ratios showed balanced Ca: Mg at M4 and elevated Mg: K at M15, with high (Ca+Mg).: K across samples.

Sample ID	Season	Ca:Mg	(Ca+Mg).: K	Mg:K	S-value (cmol^{+} kg^{-1})	T-value (cmol^{+} kg^{-1}).
M4	1	2.03	24.66	8.15	23.80	23.80
M4	2	1.80	29.61	10.59	23.87	23.87

M15	1	2.05	22.72	7.44	7.75	7.75
M15	2	1.28	37.53	16.44	23.84	23.84

4.3.4. Root nitrogen concentration

Intercropped maize had higher root nitrogen levels than sole maize across seasons (Table 4.4). In Season 1, roots nitrogen concentration averaged 0.53% in the intercrop compared with 0.46% in sole maize. In Season 2, the means were 0.43% (intercrop) and 0.40% in sole maize.

Table 4.4: Root N (%) by treatments and seasons

Treatments	Sample type	Seasons	N%
Maize intercrop	Roots	1	0.53
Sole maize	Roots	1	0.46
Maize intercrop	Roots	2	0.43
Sole maize	Roots	2	0.40

4.4. DISCUSSION

4.4.1. Nutritional quality

The substantial differences in ash and fat content demonstrate the complexity of intercropping effects on maize nutritional profiles, even though several nutritional quality parameters, such as carbohydrates, crude fiber, and dry matter, did not show significant differences between sole and intercropped maize. These results imply that although intercropping may not always improve every aspect of maize nutrition, it might result in significant changes in some nutritional components, necessitating more investigation to examine the consequences of these variations for food security and dietary quality. Recordable data values of 10.88% in Season 1 and 8.12% in Season 2 for intercropped maize and 9.61% in Season 1 and 7.87% in Season 2 for single maize, the results show that intercropped maize had a greater protein content than sole maize. The significance of these differences indicates that the intercropping technique significantly improves the protein quality of maize (Lulie *et al.,*2023). The complimentary effects of the jack bean, a leguminous crop renowned for its capacity to fix atmospheric nitrogen, are responsible for this increase in protein content.

The synthesis of amino acids, which are essential for the production of proteins in maize, is probably supported by the nitrogen provided by jack beans (Zhao *et al.,*2022). Increased protein content in intercropped maize addresses protein deficits in populations that primarily rely on maize as a staple food, improving both the nutritional profile and dietary quality (Chimoyo *et al.,*2020). However, some research has observed different results for example, Ikwunze *et al. (*2024) reported no significant variations in protein content between sole and intercropped maize on cereal production, indicating that the advantages of intercropping may range depending on crop management techniques or environmental conditions. Similar findings were also reported by Legwaila *et al. (*2022) showing that intercropping did not consistently raise protein levels in maize. This underscores the variation in results linked to various intercropping techniques.

Moisture content is another important factor that affects the overall stability and quality of maize grains, in addition to protein quality. While sole maize had moisture levels of 10.560% and 10.817%, respectively, intercropped maize had moisture contents of 10.510% in Season 1 and 10.960% in Season 2. Season 1 intercropped maize's decreased moisture content indicates improved drying conditions and moisture utilization, which can improve grain quality and lower the chance of spoiling during storage (Vanlauwe *et al.,* 2019). On the other hand, Season 2 greater moisture content in intercropped maize might be a result of climatic elements that impact crop moisture retention, like humidity and rainfall (Mucheru-Muna *et al.*, 2010).

4.4.2. Soil fertility context

Acidic conditions (pH ~5.5–5.8) can constrain P availability, yet P was high at M4 (119–125 mg kg^{-1}) and very low at M15 (as low as 5.72 mg kg^{-1}). Potassium (K) ranged from deficient to adequate (1.56–96 mg kg^{-1}). High (Ca+Mg).: K and elevated Mg:K at M15 indicate potential K uptake antagonism. These results align with season and site differences in canopy traits and yield. Intercropping maintained performance where fertility was less favorable, consistent with legume effects on nutrient cycling and rhizosphere conditions reported for cereal–legume systems. According to the evidence presented by Ananthi *et al. (*2017) on the beneficial impacts of legumes on nitrogen cycling and rhizosphere conditions in cereal–legume systems, intercropping seems to have maintained performance in less favorable fertility circumstances. For example, research by Kerr *et al., (*2007) has demonstrated that legumes can improve soil fertility by fixing atmospheric nitrogen and increasing nutrient availability, which can be especially helpful in acidic soils where nutrient availability is frequently restricted. In addition to promoting maize growth in unfavorable circumstances.

However, other research indicates that intercropping may not always result in better crop performance or nutrient availability. For instance, Moura *et al., (*2021) discovered that intercropping did not considerably improve nutrient uptake in maize in some settings, suggesting that the advantages of intercropping can be highly context dependent. In order to enhance intercropping systems for better nutrient management, these disparities highlight the need for additional research into the precise interactions between various crops and soil conditions.

4.4.3. Root nitrogen dynamics under intercropping

Intercrop increased root nitrogen (+0.07% in Season 1; +0.03% in Season 2), consistent with an N-driven explanation for higher SPAD readings, thicker stems, more kernels, and heavier 100-seed weight. While drought in Season 2 reduced the magnitude of the difference, the intercrop still maintained an N advantage. Together with soil nutrient data, these results suggest the maize–jack bean system improved N uptake and prolonged photosynthetic activity during grain fill, thereby improving key yield components and block-level grain weight.

When combined with data on soil nutrients, the increased root N levels indicate that the maize–jack bean intercropping system successfully enhanced nitrogen uptake. This increase in N availability maintained photosynthetic activity during the grain filling phase, which eventually led to higher total grain weight per block and better yield components. These findings are consistent with earlier research that emphasized the advantages of intercropping legumes to improve nutrient dynamics and encourage superior growth in companion crops (Chimoyo *et al.*, 2020).

However, some studies have observed different results, for instance, some research showed that intercropping did not significantly increase root N levels or overall nutrient uptake in maize, indicating that crop management techniques or environmental conditions may have an impact on environmental conditions (Khongdee *et al.*, 2022; Li *et al.*, 2020). These differences demonstrate the intricacy of intercropping systems and the necessity of additional study to completely comprehend the underlying mechanisms.

4.5. Conclusion

The intricate impacts of intercropping on maize's overall performance and nutritional quality are highlighted in this study, especially with regard to protein content, moisture dynamics, soil fertility, and root nitrogen uptake. For instance, people that primarily rely on maize as a staple diet, intercropping with legumes, such as jack beans, can improve some nutritional benefits and increase nutrient availability. This is demonstrated by the notable increases in protein content and fluctuations in moisture levels. The disparity in findings between several research, however, highlights the fact that the advantages of intercropping might vary depending on the context, impacted by elements like crop management techniques and environmental circumstances. The results of root nitrogen levels also provide credence to the idea that intercropping can promote nitrogen uptake, maintain photosynthetic activity and improve yield components. While many studies support these benefits, others indicate that intercropping may not always result in improved crop performance or nutrient uptake, highlighting the need for more research to identify the precise interactions between various crops and their growth environments. Overall, this study emphasizes how intercropping systems can improve agricultural sustainability and food security, but it also emphasizes the need for customized strategies to maximize these systems under varying conditions.

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CHAPTER 5

SUMMARY, SIGNIFICANCE OF FINDINGS, FUTURE RESEARCH, AND CONCLUSIONS

5.1. Summary

The study assessed field performance of maize (*Zea mays*) intercropped with jack bean (*Canavalia ensiformis)* across subtropical conditions in Mpumalanga Province, South Africa. The study focused on addressing critical challenges of food security in the region, which is caused by increased population growth, declining soil fertility, and climate unpredictability. Research revealed significant benefits of intercropping maize with jack bean. Furthermore, intercropping improved growth indicators such as leaf number, chlorophyll content, and ear length, resulting in improved yield stability. Grain quality analysis results also revealed higher protein content and overall nutritional value in the intercropped maize. Additionally, intercropping led to increased soil nitrogen levels, thereby reducing the need for chemical fertilizers and promoting sustainable agricultural. practices. Though some challenges, such as jack bean's later maturity impacting maize yields in certain conditions, the overall results demonstrate the potential of intercropping as a feasible agricultural strategy.

5.2. Significance of findings

The results of this study on maize and jack bean intercropping have significant impact on agricultural methods, food security, and environmental sustainability. Firstly, compared to sole maize, intercropped maize exhibits increased growth metrics such leaf number, chlorophyll content, and ear development, indicating that intercropping can significantly increase crop productivity (Chimoyo *et al.,*2020). This suggests that the incorporation of jack beans maximizes production potential in constrained land areas by optimizing resource consumption and supporting maize development. Secondly, the study emphasizes how important jack beans are for enhancing soil fertility through biological nitrogen fixation. The higher nitrogen levels in intercropped plots imply that this technique can lessen the detrimental impacts of monocropping-related soil nutrient depletion, ultimately promoting healthier soil ecosystems that are crucial for sustainable agriculture (Zhao *et al.,*2022).

Furthermore, the study's conclusions highlight the nutritional advantages of intercropping since jack beans give extra protein and vital elements to the diet, reducing malnutrition in areas where maize is a major staple grain (Lulie *et al.,*2023). Increased food production and higher dietary diversity are two benefits of intercropped systems, improved nutritional content of maize grains, which is essential for food security, especially for vulnerable populations. Another important finding is that intercropping systems are resilient to climate variability. This is because better soil moisture retention and less reliance on chemical fertilizers can help farmers adjust to shifting environmental conditions and promote sustainable agricultural practices (Vanlauwe *et al.,* 2019).

Additionally, smallholder farmers who frequently incur high production costs need to take advantage of the economic benefits this study highlights. According to Mucheru-Muna *et al*., (2010) intercropping is a promising technique for rural development because it can improve livelihoods and boost profitability due to the decrease in input costs and the rise in total yields. Lastly, by supporting the promotion of underutilized crops like jack beans, which can improve agricultural biodiversity and resilience, these findings add to the larger conversation on sustainable agriculture (Ayilara *et al.,* 2022). Research has proven these discoveries are significant because they have the potential to improve farming methods, influence agricultural policies, and increase food security while promoting environmental sustainability in subtropical areas.

5.3. Recommendation and Future Research

5.3.1. Recommendations for farmers

As an economical and sustainable farming method, farmers are encouraged to use maize-jack bean intercropping. This study has demonstrated that intercropping enhances crop nutrition and soil fertility in addition to raising total yields. In order to limit competition for resources and promote ideal growing circumstances, farmers should make sure that maize and jack beans are spaced appropriately. To sustain healthy crops, farmers should also receive training on efficient weed management and pest control techniques. After harvest, jack bean remains can be used as organic fertilizer to improve soil fertility for upcoming planting seasons.

5.3.2. Recommendations for extension services

Promoting intercropping systems should be a top priority for agricultural extension services' outreach and training initiatives. Farmers can learn about best practices and management strategies from demonstration farms that highlight the advantages of intercropping maize and jack beans. In order to help farmers maximize input and boost output, extension agents should also offer advice on soil testing and fertilizer recommendations specific to local conditions.

Additionally, encouraging farmer-to-farmer knowledge sharing can improve the awareness of effective intercropping techniques in rural communities.

5.3.3. Recommendations for policymakers

Intercropping systems should be incorporated into national agricultural development plans by policymakers. Supporting initiatives that offer resources and subsidies to promote smallholder farmers' adoption of sustainable practices is part of this. To increase agricultural diversity and resilience, policies that support study and development of underused crops like jack beans must be developed. The adoption and use of jack beans in regional diets can also be increased by developing awareness campaigns regarding their nutritional advantages.

5.3.4. Recommendations for further research

In order to identify the best combinations for different agro-ecological zones, future research should concentrate on optimizing intercropping systems by investigating various planting layouts, crop varieties, and management techniques. To evaluate the long-term effects of intercropping maize and jack beans on soil fertility, microbial populations, and soil health, more research is required. To give farmers a thorough understanding of the financial advantages of implementing these systems, economic evaluations comparing the profitability of intercropping to monocropping should also be carried out. Furthermore, in order to improve the jack bean's acceptability for human consumption and animal feed, research should also investigate processing techniques that lower anti-nutritional ingredients. Additionally, research on how climate change affects intercropping systems will be essential for creating adaptation plans that guarantee the resilience of farming communities in subtropical areas

In conclusion, effective maize-jack bean intercropping can greatly enhance livelihoods, food security, and sustainable agriculture. Stakeholders can cooperate to improve agricultural production and resilience in the face of persistent difficulties by concentrating on these suggestions and potential research topics.

5.4. Conclusion

The study underscores that the intercropping of maize with jack bean significantly improves agricultural productivity, environmental sustainability, and nutritional quality in subtropical farming systems. This research corroborates that intercropping can help strengthen crop yields amidst fluctuating climatic conditions while improving soil fertility through nitrogen fixation. The positive results indicated that such intercropping systems could play a pivotal role in addressing food insecurity and promoting sustainable farming practices in South Africa. Future research should focus on optimizing management practices, breeding commercial varieties of jack bean, and exploring the economic profitability of intercropping systems more extensively. Furthermore, by increasing knowledge base and encouraging policy support for these practices, it is possible to improve food security and strengthening adaptability among farming communities especially in rural areas. This research contributes beneficial insights towards the advancement of sustainable agriculture streamlined with the goals for zero hunger and climate action globally.

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APPENDICES

Appendix 1: Stomatal conductance for season 1

Source	DF	SS	MS	VR	P
Rep	2	271144	135572	3.62	<0.001
Sole Maize	4	226189	56547	1.51	0.002
Maize intercropped	4	382980	95745	2.55	0.039
Error	288	1079656	37488		
Total	299				

Appendix 2: Stomatal conductance for season 2

Source	DF	SS	MS	VR	P
Rep	2	26152	13076	1.46	0.280
Sole Maize	4	1068.516	213.703	23.80	<0.001
Maize intercropped	4	282.838	56.568	6.30	<0.001
Error	346	3106.631	37488		
Total	359				

Appendix 3: Chlorophyll content for season 1

Source	DF	SS	MS	VR	P
Rep	2	145.85	36.46	0.002	0.894
Sole Maize	4	171964.6	42991.17	480.39	<0.001
Maize intercropped	4	2415.19	603.80	6.75	<0.001

		39197.7			
Error	438	3	89.49		
Total	359				

Appendix 4: Chlorophyll content for season 2

Source	DF	SS	MS	VR	P
Rep	2	2062.3	1031.1	8.98	0.004
			144487.		
Sole Maize	4	72437.5	5	126.14	<0.001
Maize intercropped	4	8285.5	1657.1	14.43	<0.001
Error	346	39739.6	114.9		
Total	359				

Appendix 5: Ear growth length for season 1

Source	DF	SS	MS	VR	P
Rep	2	3.1211	0.7803		
			13834.7	1394.3	
Sole Maize	4	55339.14	8	7	<0.001
		1191.851	297.962		
Maize intercropped	4	3	8	529.88	<0.001
Error	438	246.2955	0.5623		
Total	449				

Appendix 6: Ear growth length for season 2

Source	DF	SS	MS	VR	P
Rep	2	27.489	13.744	3.36	

Sole Maize	4	11907.181	2381.436	582.01	<0.001
Maize intercropped	4	7249.958	1449.992	354.37	<0.001
Error	346	1415.744	4.092		
Total	359				

Appendix 7: Leaf index for season 1					
Source	**DF**	**SS**	**MS**	**VR**	**P**
Rep	2	<0.001636	0.000409	2.82	0.094
Sole Maize	4	3.092735	0.773184	100.93	<0.001
Maize intercropped	4	0.668101	0.167025	21.80	<0.001
Error	438	3.355325	0.007661		
Total	449				

Appendix 8: Leaf index for season 2					
Source	**DF**	**SS**	**MS**	**VR**	**P**
Rep	2	3.346	1.673	0.97	0.480
Sole Maize	4	8.494	1.699	0.98	0.428
Maize intercropped	4	10.174	2.035	1.18	0.320
Error	346	597.865	1.728		
Total	359	620.740			

Appendix 9: Leaf number for season 1

Source	DF	SS	MS	VR	P
Rep	2	0.054	0.014	15.74	<0.001
Sole Maize	4	7935.55	1983.889	1624.45	<0.001
Maize intercropped	4	42.848	10.712	8.77	<0.001
Error	438	534.917	1.221		
Total	449				

Appendix 10: Leaf number for season 2

Source	DF	SS	MS	VR	P
Rep	2	65.16	32.58	1.36	0.004
Sole Maize	4	872.31	174.46	7.28	<0.001
Maize intercropped	4	613.98	122.80	5.13	<0.001
Error	346	8288.74	23.96		
Total	359				

Appendix 11: Plant height for season 1

Source	DF	SS	MS	VR	P
Rep	2	38.0	9.5	24.08	<0.001
Sole Maize	4	4016032	1004008	8459.09	<0.001
Maize intercropped	4	732.5	183.1	1.54	0.189
Error	438	51986.1	118.7		
Total	449				

Appendix 12: Plant height for season 2

Source	DF	SS	MS	VR	P
Rep	2	65.16	32.58	1.36	0.004
Sole Maize	4	872.31	174.46	7.28	<0.001
Maize intercropped	4	613.98	122.80	5.13	<0.001
Error	346	51986.1	118.7		
Total	359				

Appendix 13: Cob length for season 2

Source	DF	SS	MS	VR	P
Rep	2	17.679	8.839	29.33	<0.001
Maize intercropped	2	236.038	118.019	29.33	<0.001
Error	127	510.989	4.024		
Total	359				

Appendix 14: Cob length for season 1

Source	DF	SS	MS	VR	P
Rep	2	42.956	42.956	51.55	0.088
Maize intercropped	2	2126.809	21.26.809	445.10	<0.001
Error	56	267.585	4.778		
Total	59				

Appendix 15: Cob weight for season 1

Source	DF	SS	MS	VR	P
Rep	2	0.007759	0.003879	39.31	<0.001
Maize intercropped	2	0.155269	0.077635	39.31	<0.001
Error	127	0.250806	<0.001975		
Total	131				

Appendix 16: Cob weight for season 2

Source	DF	SS	MS	VR	P
Rep	2	0.14678	0.14678	0.26	0.701
Maize intercropped	2	0.56380	056380	10.55	0.002
Error	56	2.99228	0.05343		
Total	59				

Appendix 17: Kernel count for season 1

Source	DF	SS	MS	VR	P
Rep	2	10398	5199	6.92	<0.001
Maize intercropped	2	069061	34531	6.92	<0.001
Error	127	2.99228	0.05343		
Total	131				

Appendix 18: Kernel count for season 2

Source	DF	SS	MS	VR	P
Rep	2	<0.001053	<0.001053	0.04	0.869
Maize intercropped	2	0.703117	0.703117	362.63	<0.001
Error	56	0.108580	<0.001939		
Total	59				

Appendix 19: Kernel per 100 count for season 1

Source	DF	SS	MS	VR	P
Rep	2	1.039	5.195	0.04	<0.001
Maize intercropped	2	1.332	6.660	1402.48	<0.001
Error	127	0.108580	<0.001939		
Total	131	1.393			

Appendix 20: Kernel per 100 count for season 2

Source	DF	SS	MS	VR	P
Rep	2	<0.001053	<0.001053	0.04	0.869
Maize intercropped	2	0.703117	0.703117	362.63	<0.001
Error	56	0.10850	<0.001939		
Total	59	0.836833			

Appendix 21: Moisture for season 1

Source	DF	SS	MS	VR	P
Rep	1	12.07525	12.07525	6.44	0.239
Maize intercropped	1	54.43159	54.43159	607.43	<0.001
Error	56	0.10850	<0.001939		
Total	59	7340000			

Appendix 22: Moisture for season 2

Source	DF	SS	MS	VR	P
Rep	1	12.07525	12.07525	6.44	0.239
Maize intercropped	1	54.43159	54.43159	607.43	<0.001
Error	56	5.01816	0.08961		
Total	59	73.40000			

Appendix 23: Total seed weight per treatment season 1

Source	DF	SS	MS	VR	P
Rep	2	0.01382	0.00691	6.44	0.239

Maize intercropped	2	426.09176	213.04588	5338.81	<0.001
Error	127	5.06795	0.03991		
Total	131	431.88821			

Appendix 24: Total seed weight per treatment season 2

Source	**DF**	**SS**	**MS**	**VR**	**P**
Rep	2	0.17329	0.17329	55.88	0.085
Maize intercropped	2	0.05279	0.05279	4.92	0.031
Error	56	0.60072	0.01073		
Total	59	0.82990			

Appendix 25: Ash

Source	**DF**	**SS**	**MS**	**VR**	**P**
Rep	2	0.0915	0.0457	0.28	<0.001
Sole Maize	1	4.8896	4.8896	30.31	<0.001
Maize intercropped	1	5.1221	5.1221	31.75	0.002
Error	6	8288.74	23.96		
Total	1	15.5121			

Appendix 26: Proteins

Source	**DF**	**SS**	**MS**	**VR**	**P**
Rep	2	1.2311	0.6156	1.70	<0.001
Sole Maize	4	1.7404	1.7404	4.82	0.071
Maize intercropped	4	15.1201	15.1201	41.86	<0.001
Error	6	2.1675	0.3612		

Total	11	21.0445

Appendix 27: Moisture					
Source	**DF**	**SS**	**MS**	**VR**	**P**
Rep	2	0.006017	0.003008	2.04	0.005
Sole Maize	1	0.006533	0.006533	4.43	0.080
Maize intercropped	1	0.374533	0.374533	253.92	<.001
Error	6	0.008850	<0.001475		
Total	11	0.423967			