DIVERSIFICATION OF NEGLECTED LEGUMES INTO CROPPING SYSTEMS OF SOUTH AFRICA

by

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in Discipline of Crop Science

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PREFACE

The research presented in this thesis was conducted by the candidate while based in the Discipline of Crop Science, within the School of Agricultural, Earth and Environmental Sciences, College of Agriculture, Engineering and Science, at the University of KwaZulu-Natal, Pietermaritzburg, South Africa.

This work has not been submitted to any other university, and, except where otherwise acknowledged, the findings reported herein are the result of the candidate's own investigations.

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DECLARATION 1: PLAGIARISM

I, **Busisiwe Vilakazi**, declare that:

(i) The research presented in this thesis is my original work, except where explicitly indicated or acknowledged.

(ii) This thesis has not been submitted, either in full or part, for any degree or examination at any other university.

(iii) This thesis does not include data, images, graphs, or other material from other individuals unless clearly acknowledged and properly referenced.

(iv) This thesis does not contain writing from other authors unless specifically acknowledged. Where such sources have been cited:

a) Their ideas have been paraphrased and appropriately referenced, or

b) Their exact words have been quoted within quotation marks and duly referenced.

(v) Where material used in this thesis has formed the basis of published work, my specific contributions to those publications have been clearly stated.

(vi) This thesis primarily consists of material that I have prepared, and which has been published in peer-reviewed journals. Additional supporting content has been included where necessary.

(vii) No text, graphics, or tables have been copied directly from internet sources unless explicitly acknowledged, with full details provided in the thesis and in the reference section.

Signed: Ms. Busisiwe Vilakazi (*Candidate*)

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DECLARATION 2: PUBLICATIONS

My specific contribution to each paper is clearly indicated. An asterisk (*) denotes the corresponding author.

Chapter 2

Vilakazi, B*., Mafongoya, P.L., Odindo, A.O. and Phophi, M.M., 2025. The role of neglected grain legumes in Food and Nutrition Security and Human Health. Sustainability, 17(1), p.350. DOI: https://doi.org/10.3390/su17010350 (**Impact factor = 3.6**)

Chapter 3

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Chapter 4

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ABSTRACT

Neglected legumes (Bambara groundnut, cowpea, pigeon pea) are fundamental to global food systems, contributing to agricultural sustainability, enhancing food security and strengthening the resilience of smallholder farming systems. However, they remain underutilized and have historically received limited attention in terms of cultivation, research, and market development, despite their significant nutritional, agronomic and environmental potential. Therefore, this study's objectives were (1) to assess the socioeconomic factors influencing crop diversification among smallholder farmers in Bergville, South Africa; (2) to investigate the socioeconomic factors influencing smallholder farmers' willingness to cultivate neglected legumes and their selection of suitable planting dates; (3) to determine the effect of planting date on agronomic performance of neglected legumes under rainfed conditions; and (4) to evaluate the effect of cropping systems on the adaptability of neglected legumes in rainfed conditions. The first study on the socioeconomic factors influencing crop diversification among smallholder farmers in Bergville, South Africa, revealed that farmers in the study area practice crop diversification. However, the findings indicated that, socioeconomic factors play a crucial role in shaping diversification decisions within smallholder farming systems. This study confirms that, limited access to land, water availability, market access, and education level constrain farmers' ability to diversify their crop choices. The second study findings indicate the vital role of socioeconomic factors in shaping adoption decisions and integrating these crops into existing cropping systems. Limited access to land, water availability, market access, and marital status influence farmers' willingness to cultivate neglected legumes. Household size, participation in legume-related training, and access to irrigation water influenced the selection of suitable planting dates. The limited cultivation and adoption of neglected legumes were not primarily due to resource constraints but rather a lack of awareness and knowledge regarding their nutritional and health benefits. The third study on the effect of planting date on agronomic performance of neglected legumes under rainfed conditions indicated a significant variation in agronomic performance across planting dates, with early planting generally associated with improved emergence, timely flowering, and higher yield potential while the fourth study demonstrated that cropping systems significantly influenced the adaptability of neglected legumes under rainfed conditions. Intercropping systems, particularly those involving cereal-legume combinations, have enhanced the growth performance, yield, and resource use efficiency of neglected legumes compared to sole cropping. The improved adaptability observed under intercropping is attributed to the complementary utilisation of resources and microclimatic benefits that mitigate water stress.

EXTENDED ABSTRACT

The contribution of neglected legumes to food and nutrition security remains limited due to the socio-economic challenges faced by farmers, which contribute to the underutilization of these legumes. Integrating neglected legumes into cropping systems would broaden the basket of options, and the net effect would be increasing resilience. Crop diversification is a vital strategy for achieving sustainable agriculture and food security; however, its adoption rates remain low. This study first objective examined the socioeconomic factors influencing crop diversification among smallholder farmers. A two-stage sampling procedure was employed to collect data from 161 farmers who specialised solely in crop production. A structured questionnaire was used to collect data, analysed using descriptive statistics. The multiple linear regression and multivariate probit regression models were applied to assess the socioeconomic factors influencing diversification. The results revealed that smallholders primarily focused on vegetable cultivation (87%), followed by cereals (56%) and legumes (43%). Education level, household size, market access, and the perceived benefits of diversification significantly influenced diversification decisions ($p < 0.05$). Also, sources of irrigation water, age, marital status, and farm size were key factors in vegetable diversification, while farming experience, farm size, and perceived benefits influenced legume diversification. Only marital status and farming experience were positively linked to cereal crop diversification. Furthermore, 48.4% of farmers practice intercropping, integrating maize with pumpkins or sugar beans, while 33.5% still rely on monoculture, predominantly maize, due to limited resources. These findings underscore the need for policies and extension support to address socioeconomic barriers and promote the wider adoption of crop diversification strategies. The second objective of the study was to assess socioeconomic factors influencing farmers' willingness to cultivate neglected legumes and their selection of suitable planting dates in Bergville, South Africa. A simple random sampling procedure was used to collect data from 150 farmers who specialised exclusively in crop production. An action research design was implemented, comprising structured training sessions on neglected legumes and trial demonstrations. Data were collected through a structured survey questionnaire, focus group discussions, and key informant interviews. Descriptive statistics were used for analysis, and a multivariate probit model was employed to determine the socioeconomic factors influencing farmers' willingness to cultivate neglected legumes including Bambara groundnut (*Vigna subterranea*), cowpea (*Vigna unguiculata)*, pigeon pea (*Cajanus cajan*), and common bean (*Phaseolus vulgaris*) and their selection of suitable planting dates. Findings confirmed that, the majority of smallholder farmers primarily focus on vegetable cultivation, followed by cereals, while a smaller

proportion engage in legume farming. The results also revealed that, limited knowledge and resources, along with the lack of training programs and extension services, specifically targeting neglected legumes, are significant barriers hindering their adoption and cultivation in the region. Furthermore, the study revealed that a majority of smallholder farmers had never received training in legume production. Additionally, marital status, farm size, market access, and water sources for irrigation were significant socioeconomic factors influencing farmers' willingness to cultivate neglected legumes, while household size, participation in legume training, and water sources for irrigation had a significant effect on farmers' selection of suitable planting dates. These findings underscore the need for targeted interventions, including tailored training programs, improved access to resources, and enhanced extension services, to overcome these barriers and promote the adoption of neglected legumes into smallholder farmers' cropping systems.

The third objective examined the effect of planting date on the agronomic performance of the selected neglected legume crops. Field trials were conducted over two consecutive summer growing seasons (2022/23 and 2023/24) using a split-plot randomized complete block design with three replications. Phenological traits (emergence, flowering, podding, and senescence) and yield components (pod mass, and grain yield) were recorded and analysed using GenStat® and principal component analysis. Significant effects of planting date, legume species, season, and their two- and three-way interactions ($P \leq 0.05$) were observed for all measured traits. Early planting demonstrated enhanced crop establishment and vegetative development, while reproductive traits were strongly influenced by the synchronization of phenological stages with prevailing climatic conditions. Cowpea and Bambara groundnut demonstrated stable phenological and reproductive performance across planting dates and seasons, with high emergence rates of 90.2% and 85.63%, respectively, suggesting strong resilience under climate variability. Pigeon pea showed greater sensitivity, particularly to delayed planting. Delayed sowing increased grain yield in common bean, cowpea, and Bambara groundnut, whereas pigeon pea showed a decline. These findings underscore the importance of aligning planting dates with species- specific phenological responses to optimize the productivity and resilience of neglected legumes in rainfed systems.

The fourth objective evaluated the effects of cropping systems on the adaptability of neglected legumes in rainfed environments. Field trials were conducted over two consecutive summer growing seasons (2022/23 and 2023/24) using a split-plot randomized complete block design with three replications. Phenological traits (emergence, flowering, podding, and senescence),

yield components (pods per plant, seeds per pod, pod mass, 100-seed weight and grain yield (t ha^{-1})), and land equivalent ratios (LER) were recorded and analyzed using GenStat® and principal component analysis. Significant effects of cropping system, cultivar, season, and their two- and three-way interactions ($P \leq 0.05$) were observed for all measured traits, confirming that legume-based intercropping systems significantly influenced the adaptability and productivity of neglected legumes under rainfed conditions. Intercropping enhanced early emergence and accelerated reproductive development in legumes such as Bambara groundnut, cowpea, and common bean, while pigeon pea showed reduced establishment under sole cropping due to competitive suppression. Pod production, pod mass, seed number per pod, 100-seed weight and grain yield consistently increased under intercropping. Cowpea and Bambara groundnut exhibited stable responses across seasons, whereas common bean and pigeon pea showed greater variability, highlighting the importance of genotype and species-specific compatibility with intercrop designs. Land equivalent ratios (LER) consistently exceeded 1.0 under intercropping confirming the superior land-use efficiency and yield potential of intercropping in smallholder agroecosystems. These findings underscore the importance of strategic selection of legume species with complementary phenology, growth dynamics, and resource requirements to optimize interspecific interactions and enhance system productivity.

Keywords: Smallholder farmers; socioeconomic attributes; rainfed agriculture; legumes adoption; intercropping; agronomic performance; optimal planting date; multivariate probit regression model; PCA

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Chapter 1: Introduction

1.1 Background

Addressing the second objective of the Sustainable Development Goals (SDGs), which aims to achieve zero hunger, necessitates strategies to enhance production within smallholder cropping systems (Arora and Mishra, 2022; Lile et al., 2023). This is particularly critical for mitigating food and nutrition insecurity in developing countries (World Health Organization, 2021). Food insecurity represents a pressing global challenge for policymakers, especially in Sub-Saharan Africa, where rapid population growth significantly outpaces the availability and quality of food necessary to sustain the population (Adjimoti and Kwadzo, 2018; Béné et al., 2020). Smallholder farmers play a pivotal role in ensuring food and nutrition security, and fostering sustainable rural development (Gollin, 2019). Sub-Saharan African farmers contribute approximately 80% of the region's food supply (AGRA, 2019; Touch et al., 2024). However, they face a multitude of challenges, including climate change, increased agricultural risks, declining soil fertility, environmental degradation, water scarcity, dysfunctional input-output markets, inadequate extension services, and weak policy support (Adjimoti and Kwadzo, 2018; Kamau et al., 2022). Consequently, many rural households experience declining agricultural productivity, exacerbated food and nutrition insecurity, and increased income variability, all of which have a negative impact on their livelihoods (Ghosh and Braun, 2020). Among these challenges, food and nutrition insecurity and income variability are central to the livelihoods of smallholder farmers (Touch et al., 2024). This stresses the urgent need for a comprehensive transformation of agriculture in Africa, particularly in the most affected regions, such as southern Africa. Such a transformation should aim to enhance productivity, strengthen the resilience of farming systems, improve rural livelihoods, and minimize environmental impacts (Haddad et al., 2021). Achieving these objectives will require targeted interventions, innovative policies, and sustainable practices that address the root causes of agricultural underperformance and vulnerability (Calicioglu et al., 2019).

Crop diversification serves as a critical strategy for mitigating risks in agricultural production, enhancing productivity, and addressing food and nutrition insecurity (Vernooy, 2022; Mihrete and Mihretu, 2024). It can also increase farm income, generate employment, alleviate poverty, and conserve soil and water resources within smallholder cropping systems. Crop diversification involves cultivating multiple crop varieties from the same or different species, in a given area through practices such as rotations and intercropping (Hufnagel et al., 2020). It is widely regarded as an ecologically sustainable, cost-effective, and practical approach to reducing agricultural uncertainties, particularly for smallholder farmers. Additionally, it enhances resilience and fosters greater spatial and temporal biodiversity on farms. Barman et al. (2022) highlights that crop diversification improves soil fertility, pest and disease management, yield stability, nutritional diversity, and overall health. It can also replace chemical-based solutions for maintaining soil fertility and pest control. Similarly, Balakrishnan and Nagamurugan (2020), emphasize that crop diversification provides an environmentally sustainable alternative for parasite control and soil fertility maintenance in agricultural systems. Diversified cropping systems generally exhibit greater agronomic stability and resilience due to reduced weed and insect pressures, lower dependence on nitrogen fertilizers (especially when leguminous crops are included), reduced erosion through cover cropping, improved soil fertility, and increased yields per unit area. The resilience of diversified systems is further enhanced by their capacity to adapt to climate change. Unlike monoculture systems, diversified farms leverage local flora to sequester carbon, reducing carbon dioxide emissions. This contributes to climate-smart agriculture by promoting productivity, improving livelihood outcomes, enhancing system resilience, and mitigating greenhouse gas emissions (Kamyab et al., 2024). Despite crop diversification's clear ecological, agronomic, and socioeconomic benefits, public policies and development initiatives often provide inadequate support for its adoption. Strengthening policy frameworks and incentivizing diversification practices are essential to harness the full potential of this approach in addressing the challenges of sustainable agriculture and climate adaptation.

To effectively address the impacts of climate change, smallholder farmers must adopt adaptive production and farm management practices (Harvey et al., 2018; Ojo et al., 2021). These include adjusting planting dates, practising intercropping, implementing conservation agriculture, utilizing crop and seed storage infrastructure, and transitioning to more climate-resilient crops or crop varieties. Climate-resilient crops enhance tolerance to biotic and abiotic stresses while improving yields under adverse conditions (Cabusora, 2024). These crops provide a critical mechanism for adapting to the challenges posed by drought, elevated temperatures, and other climate-related stresses. Adopting climate-resilient crop varieties, such as drought-tolerant legumes and early maturing cereal crops with improved salinity tolerance, enables smallholder farmers to better withstand climate shocks (Acevedo et al., 2020). Climate-resilient neglected legumes have proven effective in enhancing resilience due to their ability to thrive under challenging environmental conditions. These include Bambara groundnut (*Vigna subterranea*), cowpea (*Vigna unguiculata*) and pigeon pea (*Cajanus cajan*). Despite their demonstrated benefits, adoption rates of such crops remain suboptimal in certain cropping systems. This is particularly evident in rural areas with high concentrations of smallholder farmers relying heavily on rain-fed agriculture for sustenance and income. Increasing the adoption of climate-resilient crops will require targeted interventions, such as improved access to quality seeds, capacity-building programs, enhanced market integration, and supportive policies tailored to the needs of smallholder farmers. These measures are essential for fostering greater resilience and sustainability in agricultural systems affected by climate variability.

Neglected legumes offer substantial potential to enhance human nutrition and health while adhering to principles of environmental sustainability (Vilakazi et al., 2025). These legumes are rich sources of high-quality protein, macronutrients, micronutrients, vitamins, essential amino acids, carbohydrates, starch, dietary fibre, and sugars. They are also characterized by low-fat content and an absence of cholesterol. Additionally, neglected legumes contain essential phytochemicals, antioxidants, and bioactive compounds that contribute to reduced risks of major chronic diseases and associated mortality factors, including cardiovascular disease, diabetes, cancer, obesity, and gastrointestinal disorders (Barman et al., 2018; Vilakazi et al., 2025). Despite these recognized benefits, the contribution of neglected legumes to food and nutrition security remains limited. This has resulted in an overreliance on a narrow range of legumes, such as common beans, soybean, groundnut, pea and lentil, which often exhibit poor resilience to climatic stresses. This reliance poses significant risks to the sustainability of food production within smallholder cropping systems. Consequently, food and nutritional insecurity and related human health concerns persist in many developing regions, including South Africa. While crop diversification has been extensively studied, particularly in Asia, its connection to food security in East Africa south of Ethiopia, South Africa, the Sahel, and the Mediterranean coast of Morocco and Algeria has received comparatively less attention (Waha et al., 2018). To address this knowledge gap in South Africa, intercropping practices, including maize and neglected legumes, such as Bambara groundnut, pigeon pea, cowpea, and common bean, were implemented in smallholder cropping systems during the summer seasons of 2022/23-2023/24.These intercropping systems, conducted under rainfed conditions with varying planting dates aimed to unlock the potential of these underutilized crops. By integrating neglected legumes into cropping systems, this approach seeks to enhance food and nutrition security, improve resilience to climatic perturbations, and promote sustainable agricultural practices in developing regions.

1.2 Problem statement

Smallholder cropping systems in South Africa face increasing challenges related to declining soil fertility, climate variability, and economic instability. These challenges have reduced agricultural productivity and resilience, exacerbating food insecurity and poverty in rural communities. The reliance on a narrow range of staple crops, such as maize, has further intensified these issues by depleting soil nutrients and limiting dietary diversity. Moreover, legume diversity in smallholder farming systems is limited, primarily consisting of a few species, with the common bean being the most extensively cultivated. Neglected grain legumes, such as cowpeas, Bambara groundnuts, and pigeon peas, have the potential to address these challenges due to their adaptability to diverse agroecological conditions, ability to fix atmospheric nitrogen, and nutritional richness. Despite these benefits, their cultivation in smallholder cropping systems remains limited. Factors contributing to their underutilization include a lack of research on their agronomic performance, inadequate integration into local cropping systems, insufficient market development, and policy support. The limited diversification of smallholder cropping systems with neglected grain legumes perpetuates a cycle of low productivity, environmental degradation, and vulnerability to climate change. Addressing this gap requires a better understanding of how these legumes can be effectively incorporated into smallholder cropping systems to enhance agricultural sustainability, improve food security, and increase farmer incomes.

1.3 Justification

Diversifying neglected grain legumes into cropping systems in South Africa is essential for addressing critical challenges related to food security, environmental sustainability, and rural development. Their nutritional richness can contribute to balanced diets, particularly in regions where malnutrition and food insecurity persist. Moreover, their resilience and low input requirements promote sustainable farming practices and enhance the productivity of smallholder farmers, who form the backbone of the country's rural economy. This study aims to generate actionable insights for policymakers, researchers, and farmers by investigating the integration of these legumes into South Africa's cropping systems. The findings will contribute to the development of sustainable agricultural models, improve soil health, diversify farmers' incomes, and enhance dietary diversity. Furthermore, the study supports both national and global sustainable development agendas, including combating hunger (SDG 2), promoting responsible production (SDG 12), and addressing climate action (SDG 13). Focusing on neglected grain legumes, this research emphasizes the importance of rediscovering underutilized crops as solutions to modern agricultural challenges. This research aims to address these critical gaps by evaluating the potential of neglected grain legumes to diversify smallholder cropping systems in South Africa. It seeks to assess their agronomic performance, adaptability, and smallholder farmers' willingness to adopt these legumes, providing evidence-based solutions to build more resilient and sustainable farming systems.

1.4 Aim of the study

To promote the diversification and integration of neglected legumes into smallholder cropping systems by evaluating their agronomic performance and adaptability under rainfed conditions, identifying socioeconomic factors influencing crop diversification, as well as smallholder farmers' willingness to cultivate neglected legumes and their preferences for suitable planting dates.

1.5 Research questions

i. What are the socioeconomic factors influencing crop diversification among smallholder farmers in Bergville, KwaZulu Natal, South Africa?
ii. What are the socioeconomic factors influencing smallholder farmers' willingness to cultivate neglected legumes and their selection of suitable planting dates?
iii. How do planting dates affect the growth, yield, and performance of neglected legumes under rainfed conditions?
iv. How do various cropping systems influence the adaptability and performance of legumes under rainfed conditions?

1.5.1 Specific objectives

The specific objectives of the study were:

i. To assess the socioeconomic factors influencing crop diversification among smallholder farmers in Bergville, KwaZulu Natal, South Africa.
ii. To investigate the socioeconomic factors influencing smallholder farmers' willingness to cultivate neglected legumes and their selection of suitable planting dates.
iii. To determine the effect of planting date on agronomic performance of neglected legumes under rainfed conditions.
iv. To determine the effect of cropping systems on the adaptability of neglected legumes in rainfed conditions.

1.6 Thesis outline

Chapter 1: Introduction

This chapter provides an overview of smallholder cropping systems and emphasizes the critical need for transformative strategies, including the diversification of neglected legumes, to enhance agricultural productivity, strengthen climate resilience, and improve rural livelihoods while minimizing environmental impacts. Additionally, the chapter outlines the research aims, objectives, problem statement, and justification of the study.

Chapter 2: The role of neglected grain legumes in food and nutrition security and human health: A review.

This chapter provides a comprehensive review of the literature on utilizing neglected grain legumes to enhance food and nutritional security and their contributions to human health. It identifies key knowledge gaps that should be prioritized in research strategies to develop sustainable food systems in sub-Saharan Africa.

Chapter 3: Socioeconomic Factors Influencing Crop Diversification Among Smallholder Farmers in Bergville, South Africa.

This chapter assesses the socioeconomic factors that influence the adoption of crop diversification practices within smallholder cropping systems. It further identifies the extent and patterns of crop diversification among smallholder farmers in Bergville, South Africa.

Chapter 4: Socioeconomic factors influencing smallholder farmers' willingness to cultivate neglected legumes and their selection of suitable planting dates.

This chapter examines the socioeconomic determinants that shape smallholder farmers' willingness to cultivate neglected legume species and their preferences for suitable planting dates. It focuses on identifying the key drivers of acceptance and adoption and evaluates how these factors influence decision-making at the farm level and across broader agricultural practices. The insights gained aimed to inform the development of targeted strategies to promote the integration of neglected legumes into smallholder farming systems.

Chapter 5: Effect of planting date on agronomic performance of neglected legumes under rainfed conditions.

This chapter determines the optimal planting dates for maximizing the productivity of neglected legumes in rainfed farming systems.

Chapter 6: Cropping systems effect on the adaptability of neglected legumes in rainfed conditions.

This chapter investigates the cropping systems that enhance the climate resilience and efficiency of neglected legume cultivation in rainfed farming.

Chapter 7: Conclusions and recommendations

This chapter provides a comprehensive conclusion of the findings from the experimental chapters, highlighting their implications. It also presents conclusions and outlines recommendations to farmers and future research.

References

Acevedo, M., Pixley, K., Zinyengere, N., Meng, S., Tufan, H., Cichy, K., Bizikova, L., Isaacs, K., Ghezzi-Kopel, K. and Porciello, J., 2020. A scoping review of adoption of climate-resilient crops by small-scale producers in low-and middle-income countries. Nature plants, 6(10), pp.1231-1241.

Adjimoti, G.O. and Kwadzo, G.T.M., 2018. Crop diversification and household food security status: evidence from rural Benin. Agriculture & Food Security, 7(1), pp.1-12.

AGRA, 2019. Africa Agriculture Status Report: The Hidden Middle: A Quiet Revolution in the Private Sector Driving Agricultural Transformation (Issue 7). Available online at: https://agra.org/wp-content/uploads/2019/09/AASR2019-The-Hidden-Middleweb.pdf

Arora, N.K. and Mishra, I., 2022. Current scenario and future directions for sustainable development goal 2: A roadmap to zero hunger. Environmental Sustainability, 5(2), pp.129-133.

Balakrishnan, B. and Nagamurugan, N., 2020. Protection of Indian Traditional Rice Varieties: Role of PPV and FRA. In Intellectual Property Rights and the Protection of Traditional Knowledge (pp. 158-181). IGI Global.

Barman, A., Marak, C.M., Barman, R.M. and Sangma, C.S., 2018. Nutraceutical properties of legume seeds and their impact on human health. In Legume seed nutraceutical research. DOI: 10.5772/intechopen.78799.

Barman, A., Saha, P., Patel, S. and Bera, A., 2022. Crop diversification an effective strategy for sustainable agriculture development. In Sustainable crop production-recent advances. IntechOpen: London, UK, 2022; ISBN 978-1-80355-696-3.

Béné, C., Fanzo, J., Prager, S.D., Achicanoy, H.A., Mapes, B.R., Alvarez Toro, P. and Bonilla Cedrez, C., 2020. Global drivers of food system (un) sustainability: a multi-country correlation analysis. PloS one, 15(4), p.e0231071.

Cabusora, C.C., 2024. Developing climate-resilient crops: adaptation to abiotic stress-affected areas. Technology in Agronomy, 4(1).

Calicioglu, O., Flammini, A., Bracco, S., Bellù, L. and Sims, R., 2019. The future challenges of food and agriculture: An integrated analysis of trends and solutions. Sustainability, 11(1), p.222.

Ghosh, K. and Braun, G., 2020. Transforming food and agriculture to achieve the Sustainable Development Goals (SDGs): Good practices from FAO-GEF projects around the world. Food & Agriculture Org.

Gollin, D., 2019. IFAD Research Series No. 34-Farm Size and Productivity: Lessons from Recent Literature. IFAD research series, 34, p.2018.

Haddad, F.F., Ariza, C. and Malmer, A., 2021. Building climate-resilient dryland forests and agrosilvopastoral production systems: An approach for context-dependent economic, social and environmentally sustainable transformations. Food and Agriculture Organization.

Harvey, C.A., Saborio-Rodríguez, M., Martinez-Rodríguez, M.R., Viguera, B., Chain-Guadarrama, A., Vignola, R. and Alpizar, F., 2018. Climate change impacts and adaptation among smallholder farmers in Central America. Agriculture & Food Security, 7(1), pp.1-20.

Hufnagel, J., Reckling, M. and Ewert, F., 2020. Diverse approaches to crop diversification in agricultural research. A review. Agronomy for Sustainable Development, 40(2), p.14.

Kamau, J.W., Schader, C., Biber-Freudenberger, L., Stellmacher, T., Amudavi, D.M., Landert, J., Blockeel, J., Whitney, C. and Borgemeister, C., 2022. A holistic sustainability assessment of organic (certified and non-certified) and non-organic smallholder farms in Kenya. Environment, Development and Sustainability, 24(5), pp.6984-7021.

Kamyab, H., SaberiKamarposhti, M., Hashim, H. and Yusuf, M., 2024. Carbon dynamics in agricultural greenhouse gas emissions and removals: a comprehensive review. Carbon Letters, 34(1), pp.265-289.

Lile, R., Ocnean, M., Balan, I.M. and KIBA, D., 2023. Challenges for zero hunger (SDG 2): Links with other SDGs. Transitioning to Zero Hunger. Chapter, MDPI, pp.9-66.

Mihrete, T.B. and Mihretu, F.B., 2024. Crop Diversification for Ensuring Sustainable Agriculture, Risk Management and Food Security. Global Challenges, p.2400267.

Ojo, T.O., Ogundeji, A.A. and Belle, J.A., 2021. Climate change perception and impact of on-farm demonstration on intensity of adoption of adaptation strategies among smallholder farmers in South Africa.

Touch, V., Tan, D.K., Cook, B.R., Li Liu, D., Cross, R., Tran, T.A., Utomo, A., Yous, S., Grunbuhel, C. and Cowie, A., 2024. Smallholder farmers’ challenges and opportunities: Implications for agricultural production, environment and food security. Journal of Environmental Management, 370, p.122536.

Vernooy, R., 2022. Does crop diversification lead to climate-related resilience? Improving the theory through insights on practice. Agroecology and Sustainable Food Systems, 46(6), pp.877-901.

Vilakazi, B., Mafongoya, P.L., Odindo, A.O. and Phophi, M.M., 2025. The Role of Neglected Grain Legumes in Food and Nutrition Security and Human Health. Sustainability, 17(1), p.350.

Waha, K., Van Wijk, M.T., Fritz, S., See, L., Thornton, P.K., Wichern, J. and Herrero, M., 2018. Agricultural diversification as an important strategy for achieving food security in Africa. Global change biology, 24(8), pp.3390-3400.

World Health Organization, 2021. The State of Food Security and Nutrition in the World 2021: Transforming food systems for food security, improved nutrition and affordable healthy diets for all (Vol. 2021). Food and Agriculture Organization.

Chapter 2: The Role of Neglected Grain Legumes in Food and Nutrition Security and Human Health: A Review

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Abstract

Increasing demand for nutritious, safe, and healthy food, including the need to preserve biodiversity and other resources, signifies a prodigious challenge for agriculture, which is already at risk from climate change. Diverse and healthy plant-based diets may significantly reduce food insecurity, malnutrition, diet-related diseases, and other health-related issues. More attention to agricultural systems diversity is mandatory to improve the economic, environmental, ecological, and social sustainability of food production in developing countries. In this context, neglected legume such as Bambara groundnut (*Vigna subterranea*), cowpea (*Vigna unguiculata*) and pigeon pea (*Cajanus cajan)* could significantly provide nutritional and healthy benefits for people while adhering to sustainability principles.in add However, the contribution of neglected legumes to food and nutrition security is still limited due to socio-economic challenges faced by farmers that contribute to the underutilization of neglected legumes. Integrating neglected legumes into cropping systems would broaden the basket of options, and the net effect would be increasing resilience. These crops provide ecosystem services and promote biodiversity but face economic challenges due to limited market demand and underdeveloped value chains. Consequently, food nutritional insecurity and human health concerns remain prevalent, especially in developing countries. There is an urgent need to promote neglected legumes in agricultural systems through policy change implementation, genetic improvement, and development, fostering international cooperation to share knowledge, technologies, and best practices in the production and utilization of neglected legumes. This review comprehensively explores the utility of neglected legumes for food, nutritional security, and human health. It identifies knowledge gaps that should be prioritized as part of re-search strategies for sustainable future food systems in sub-Saharan Africa.

Keywords: bioactive compounds; climate change; dietary diversity; malnutrition; protein security; sustainable food production

2.1 Introduction

Approximately two billion people worldwide, primarily children, suffer from micronutrient deficiencies. This results in 151 million stunted children under the age of five and millions more with delayed cognitive development [1,2]. World hunger in-creased in 2020 during the COVID-19 pandemic [3]. Over one-third of the world's undernourished people reside in Africa (282 million) and Asia (418 million). In 2020, 2.37 billion people did not have access to adequate food, and this has increased by 320 million since 2019 [3]. Subsequently, malnutrition is projected to affect more than half of the world's population within the next few decades [4]. Due to the high levels of food insecurity, the sustainable development goals of achieving zero hunger, good health, and well-being will not be accomplished by 2030 [5]. These demand the use of neglected legumes to supplement diets with vital nutrients, including vitamins, minerals, carbohydrates, amino acids, and dietary fibre.

Neglected legumes are domesticated crops with useful traits but are less important than the main global crops because of limitations in supply and use [6]. Their key characteristics are their innate qualities, which enable them to greatly replenish the soil, increase food and protein security, and resist the effects of abiotic stress and climate change [7]. These neglected legumes include marama bean, horse gram, rice bean, grass pea, moth bean, tepary bean, Andean lupin, pigeon pea, Bambara groundnut, and cowpea. They currently lack a common international and well-established value chain. They are solely of regional significance in geographic, social, or economic aspects [8]. However, they play a critical role in the food system for both human and animal consumption. They have the potential to alleviate malnutrition and hidden hunger through nutritious, inexpensive, climate-resilient, and smart-agricultural food systems [9,10]. Neglected legumes are widely regarded as the most affordable plant-based sources of dietary protein, carotenoids, polyphenols, and high-energy sources that are low in glycemic index, fat, and cholesterol. Their seed content and structure provide a nutritionally beneficial matrix for the entire meal [11]. They also contain essential phytochemicals, antioxidants, and bioactive non-nutrients that play an increasingly important role in improving humans' health and helping reduce the risk of mortality due to their advantages against major chronic diseases and associated risk factors, such as cardiovascular disease, diabetes, cancer, obesity, and gastrointestinal health [11-13].

Integration of neglected legumes in production systems could play an essential role in replacing imported grain legumes in the future through providing multiple ser-vices in line with sustainability principles due to their capacity to improve soil fertility, symbiotic nitrogen fixation, and mitigation of greenhouse gas emissions [10,14]. Their extensive adaptation to poor soils and tolerance to biotic and abiotic environmental stresses compared to major legumes could potentially improve the livelihoods of smallholder farmers globally [15,16]. In the context of climate change, as diversification crops in agroecosystems, they can break the cycle of pests and diseases and contribute to balancing the deficit in plant protein production worldwide [16,17]. As a result, producing more protein from neglected legumes as an alternative to livestock protein for human consumption will lead to a reduced carbon footprint.

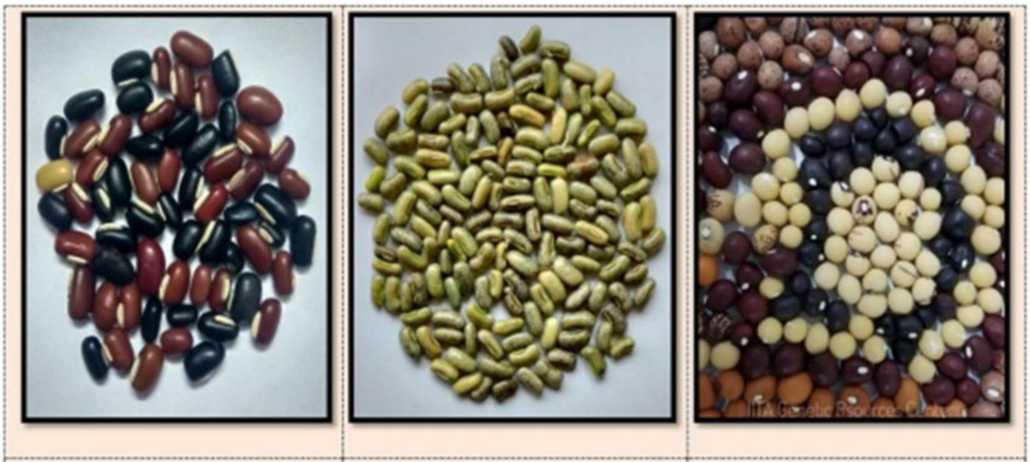
Despite their significance for the subsistence of African countries, neglected legumes remain poorly documented, with a feeble or lack of official seed supply systems [16]. This negligence has resulted in a lack of genetic improvement, which has resulted in lower yields in both quality and quantity. Moreover, dependence on neglected legumes raises intrinsic agronomic, ecological, nutritional, and economic concerns, and it is projected to be unsustainable over the long term, particularly considering the effects of climate change [18]. Hence, a global threat exists because of the discrepancy be-tween the amount of food available and the nutritional requirements of the human population. Therefore, there is a pressing need to promote the production and utilization of neglected legumes to improve the economic, environmental, and social sustainability of food production in developing countries. As a result, this will significantly contribute to securing food security and meeting the nutritional demand of an ever-increasing world population. This review provides comprehensive information on the potencies of neglected legumes for food, nutritional security, and human health, and will aid in defining the priorities for future research.

2.2 Overview of Neglected Legumes

Neglected legumes are considered minor crops that originated in Sub-Saharan Africa (Table 2.1; Figure 2.1) and are already cultivated but underutilized globally, with a relatively low global production and market value. Some of these crop species may be widely distributed globally but are limited to local production and consumption. Hence, meeting food and nutrition requirements and alleviating hunger in rural households [19]. They are grown for fodder, oil, and as sources of traditional medicine, which play a significant role in the subsistence of local communities. Neglected legumes are highly adapted to varying ecogeographical settings, withstanding conditions such as heat, drought, frost, and cold. They perform well in cropping systems with limited or no external inputs (Figure 2.2), but their utility and cultivation requirements are inadequately documented [6,8]. They are also essential in crop rotation strategies to fertilize agricultural soils. These attributes could be scientifically explored for enhancing crop improvement and promoting sustainable utilisation. However, neglected legumes have received minimal attention from researchers, plant breeders, growers, policymakers, decision-makers, traders, technology providers, and consumers due to several factors, including agronomic, genetic, economic, and social factors [5, 16, 20].

The neglected legume species include tepary bean (*Phaseolus acutifolius*), marama bean (*Tylosema esculentum*), horse gram (*Macrotyloma uniforum*), grass pea *(Lathyrus sa-tivus*), Bambara groundnut (*Vigna subterranea*), Andean lupin/Tarwi (*Lupinus mutabilis*), hyacinth bean (*Lablab purpureus*), adzuki bean (*Vigna angularis*), rice bean (*Vigna angularis*), moth bean (*Vigna aconitifolia*), pigeon pea (*Cajanus cajan*), and cowpea (*Vigna unguiculata*) [6,20], as presented in Table 2.1. Based on their utilization and industrial and economic values, the major legumes that are extensively researched, well documented, and widely cultivated with well-defined agronomic practices include soybean (*Glycine max*), common bean (*Phaseolus vulgaris*), groundnut (*Arachis hypogaea*), chick-pea (*Cicer arietinum*), and pea (*Pisum sativum*). These major legumes exhibit poor resilience to climatic perturbations, despite being widely cultivated and dominating international markets [21]. It is becoming clear that supplementing major legumes with lesser-known legumes is a viable strategy for sustainably addressing issues of food and nutrition insecurity, as well as human health. Their promotion as complementary alternative food sources in agriculture will potentially replace imported grain legumes in the future, thus improving the economic, environmental, ecological, and social sustainability of food production in developing countries. In addition, their adoption as potential alternatives for establishing resilience in smallholder farming systems will contribute to achieving zero hunger, improve consumer health, and alleviate poverty. This is because neglected legumes are easy to grow, as seeds can be locally sourced and they have low requirements for inorganic fertilisers, irrigation water, pesticides, and other inputs. However, the yield potential of neglected legumes remains low due to limited investment in genetic improvement and agronomic research, which constrains their large-scale adoption. Moreover, protein-calorie malnutrition is prevalent in many developing countries in the tropics and sub-tropics. Incorporating neglected legumes into the diet can serve as a safety net to address the challenges of malnutrition and alleviate nutrient deficiencies. The enhancement and improvement of protein supply to meet the growing demand of the population necessitate the utilisation of unconventional protein sources for further use in Sub-Saharan Africa. Harnessing the untapped nutritional and genetic potential of neglected crops has been regarded as one of the prime strategies for improving food and nutritional security in Africa over the last decade

[22]. Therefore, considerable research is still required to document the nutritional and nutraceutical advantages for both species and varieties.



A Adzuki bean **B** Rice bean **C** Bambara groundnut

D Cowpea **E** Hyacinth bean **F** Horse gram

Figure 2.1: Images of neglected legumes (Pictures no. (A–F)); Source [22].

Table 2.1: Origin and distribution of neglected legumes

Legume	**Origin and Distribution**	**References**
Tepary bean (*Phaseolus acutifolius*)	Central Mexico to Southwestern United States	[23,24]
Marama bean (*Tylosema esculentum*)	Native to Kalahari Desert, Southern Africa arid areas (Namibia, Botswana, South Africa)	[25,26]
Horse gram (*Macrotyloma uniflorum*)	Native to Southern Asia (India) and tropical Africa	[27,28]
Bambara groundnut (Vigna *subterranean*)	Sub-Saharan African countries (from the Sahara to South Africa and Madagascar)	[29,30]
Andean lupin (*Lupinus mutabilis*)	South America, Columbia, north Argentina	[31,32]
Hyacinth bean (*Lablab purpureus*)	Originated from Africa, distributed to India	[33]
Adzuki bean (*Vigna angularis*)	East Asian countries (Korea, China, Japan)	[34,35]
Rice bean (*Vigna umbellate*)	Native of South and Southeast Asia, USA, Australia, East Africa, Java, Fiji, Bangladesh, and Nepal	[36]
Cowpea (*Vigna unguiculata*)	West Africa, Asia, Southern Europe, Southern America, Central and South America	[37,38]
Moth bean (*Vigna aconitifolia*)	India, Pakistan, southern China, and Southwestern America	[39]
Grass pea (*Lathyrus sativus*)	South Asia, Sub-Saharan Africa, Mediterranean region	[40]
Pigeon pea (*Cajanus cajan*)	Originated in India, spreading to East and West Africa, Southeast Asia, Latin America, and Caribbean	[41,42]

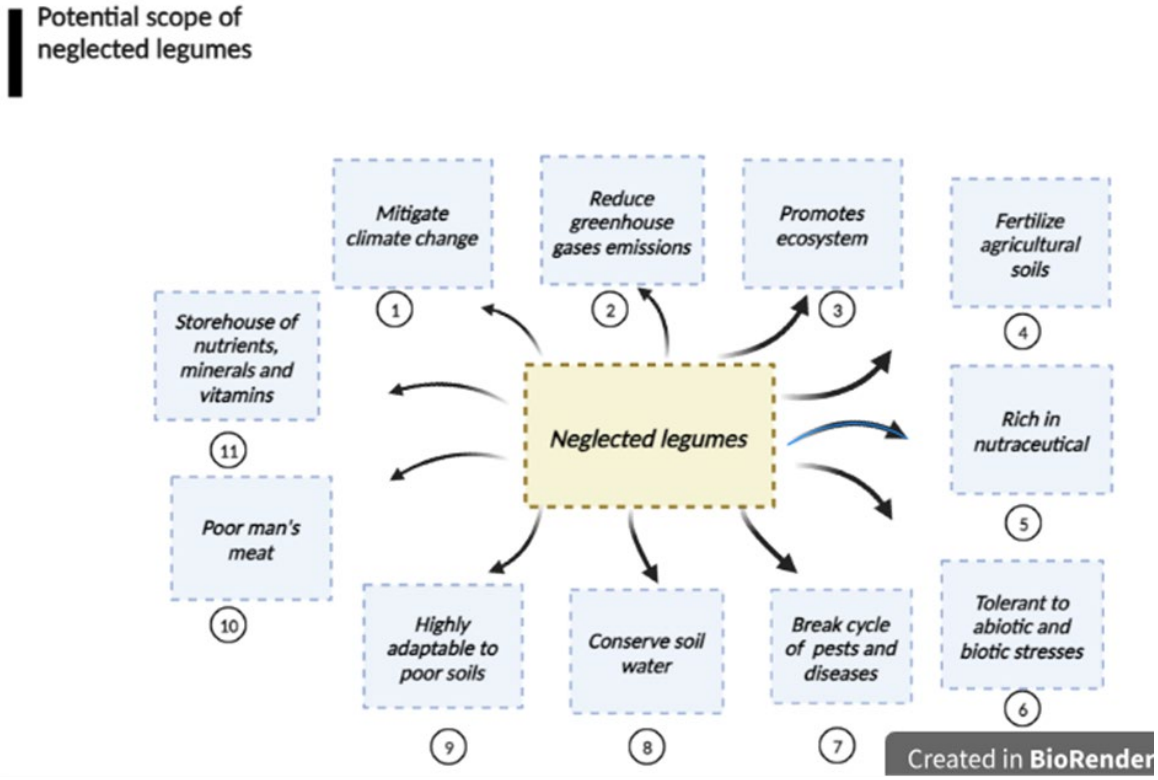


Figure 2.2: Potential scope of neglected legumes' inclusion into cropping systems.

2.3 Production of Neglected Legume Crops

In terms of production and cultivated areas, neglected legumes lag significantly behind cereal crops. In sub-Saharan Africa, only 27 million hectares are allocated for planting legume crops, with an estimated annual production of about 19 million metric tons [43]. These legumes are produced at less than 1 million metric tons per hectare, which is below the anticipated worldwide yield. The yield gap exists because legumes are considered secondary crops to cereals in terms of consumer preferences, and research activities have thus focused more on cereal production [44]. Limited attention from research and development programs, the use of unimproved varieties, a lack of quality seeds, and a lack of knowledge about cultivation, use, and nutritional value also contribute to the gap in legume production systems [45, 46]. Legumes cultivation depends not only on the effect of farmers' choices. However, they play a key role not only in such decisions but also in policymakers, who are responsible for providing practical strategies to support the inclusion of legumes in cropping systems.

Nutrition policies have not focused on creating awareness among people about the importance of dietary diversity and the addition of neglected legumes to their food basket [47]. Hence, the high demand for cereals has pushed legume production to marginal environments characterized by low rainfall and poor soils, a characteristic of most smallholder and communal farming systems. Production of legumes in developing countries, particularly in Africa, is practiced by smallholder farmers whose average household head age is 48 years; average schooling is less than 4 years; the average area of land under grain legumes is less than 0.2 ha; and arable landholdings are fragmented mainly due to the insecure land tenure systems [48]. Hence, neglected legumes are primarily produced by vulnerable and marginalized groups with limited skills and technology to produce and process them into nutritious food products [43]. They are grown primarily as secondary crops, intercropped with cereals, and occasionally used as rotational crops with cereals due to their significant role in biological nitrogen fixation. As a result, the yield and production of neglected legumes have stagnated in most developing countries over the past few decades. To achieve greater economic gain, impoverished farmers have begun to cultivate important staple crops instead of neglecting legumes. Cash crops, such as soybeans, peanuts, and chickpeas have largely replaced them.

2.3.1 Bambara Groundnut (Vigna subterranean)

The leading producers of Bambara groundnut include Nigeria, Burkina Faso, Ivory Coast, Ghana, Mali, Senegal, and Niger in West Africa; Tanzania, Malawi, Zambia, and Madagascar in Eastern Africa; and Chad and DR Congo in Central and South Africa (Figure 2.3).

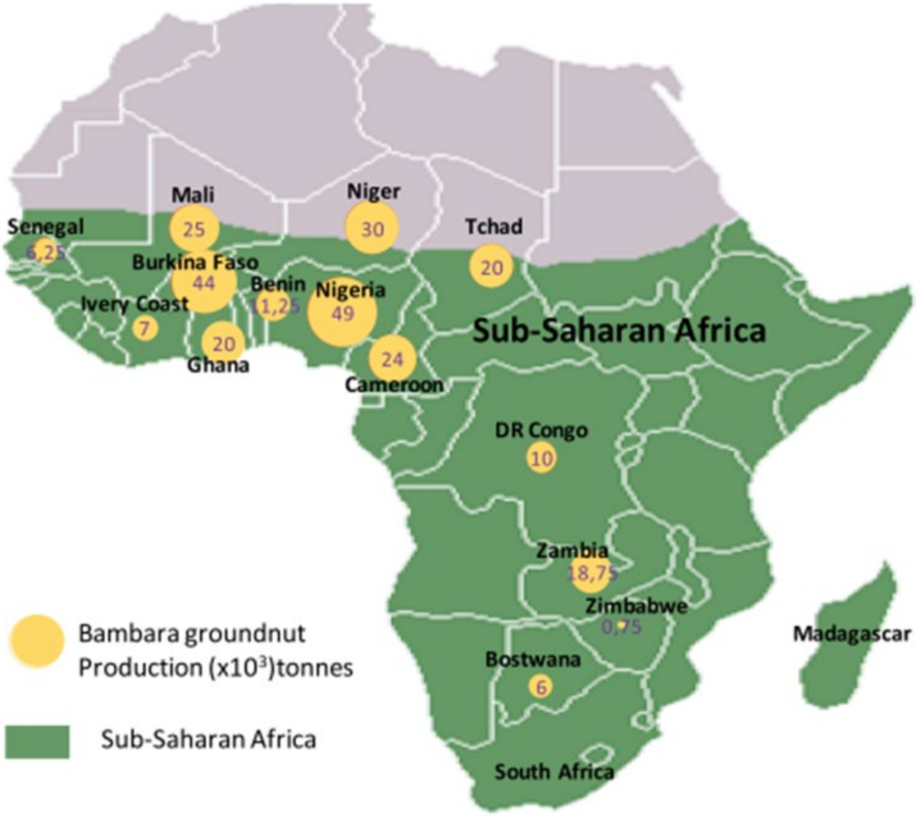


Figure 2.3: Bambara groundnut leading producers and annual production [29].

An estimated 330,000 metric tons of Bambara groundnut are produced in Sub-Saharan Africa annually, with 40% to 45% of this amount being produced in West Africa [29]. In comparison to groundnut (estimated at 37.1 million metric tons) and cowpea (estimated at 89.86-91.25 million metric tons), the global production is modest [49]. Figure 2.3 provides an overview of the annual output figures for certain countries. Yield can range from 900 kg/ha to 1200 kg/ha. The production of Bambara groundnut is considered low globally, and on-farm yields are unstable.

2.3.2 Cowpea (Vigna unguiculata)

Cowpea is produced on approximately 12 million hectares worldwide annually, amounting to about 8.986 million metric tons. Over the past three decades, cowpea production has increased globally at an average annual rate of 5%, with yearly growth in production area of 3.5% and yield growth of 1.5%. Area expansion accounted for 70% of the overall growth during this period. West Africa is the primary region for cowpea and Bambara groundnut production. Over 80% of cowpea production in Africa is produced in West Africa, mainly in Nigeria, Niger, Burkina Faso, Mali, and Senegal. This continent accounts for around 84% of the world’s cowpea-producing area and 83.4% of the crop’s total global production. Despite the significance of cowpea, Sub-Saharan African farmers only produce less than 650 kg/ha of the crop annually, compared to a potential output of around 2000 kg/ha [15].

2.3.3 Horse Gram, Andean Lupin, and Other Neglected Legumes’ Production

Horse grams are produced globally at a rate of 1.725.395.71 tons and 1407.2 kg/ha, comparable to Andean lupin at 1.384.963.65 tons and a rate of 6218.9 kg/ha. Andean lupin production is mostly concentrated in South America’s Andes region, particularly in Ecuador, Chile, Peru, and Bolivia. According to [50], Australia contributes 1.1 million metric tons to global production. However, sub-Saharan Africa produces a relatively small quantity of Andean lupins, with the majority coming from South Africa, Kenya, and Tanzania. Andean lupin is not yet regarded as a commercial crop due to several challenges to its adoption, including a long cropping cycle, poor and unstable yield production, and prevailing issues regarding the crop’s integration into local agricultural systems as a result of biotic and abiotic stresses [50].

China is the world’s biggest producer of adzuki beans, producing 0.9 million metric tons with a productivity of 1100 kg/ha [51]. Rajasthan has 0.22 million metric tons of moth beans, almost 85% of the world’s total production. The yield is estimated to be between 70 and 270 kg/ha, which is low. Experimental seeds can yield up to 2600 kg/ha in Australia and the United States [52]. This highlights the need to enhance breeding efforts for these underutilized legumes. Globally, 787.29 million metric tons of rice beans are produced each year. Asia produces the most, with 708.15 million metric tons annually, followed by Oceania (437.147.28 million metric tons), Africa (37.19 million metric tons), South and North America (602.211.52 million metric tons), and Europe (3.78 million metric tons).

2.3.4 Production of Marama Bean, Grass Pea and Pigeon Pea

2.3.4.1 Marama Bean (Tylosema esculentum)

The marama bean is a native crop of the Kalahari Desert in South Africa, with a yield potential of 2 tons per hectare. In Namibia and Botswana, it grows naturally. As a result, only a few farmers produce marama beans on small plots, with a total farmed land area of about 50 hectares. In Australia, Israel, Kenya, and the United States of America, the marama bean is undergoing experimental cultivation (Omotayo and Aremu, 2021) [53]. The crop is also barely grown in Zambia and Mozambique, while it is found in South Africa's provinces such as the Northwest, Northern Cape, Limpopo, and Gauteng. Marama bean production is limited by several factors, including the lengthy seed-to-seed cycle, which prompts farmers to prefer early maturing varieties. Therefore, resolving this problem becomes a fundamental breeding goal. The low seed output is another drawback, which is currently the focus of major selection breeding research (Chimwamurombe and Naomab, 2024) [26]. In addition to lobbying governments and donor organizations for inclusion in seed production and breeding pro-grams, overcoming these obstacles would make it easier to promote marama bean cultivation as a conventional crop.

2.3.4.2 Grass Pea (Lathyrus sativus)

Approximately 1.20 million tons of grass peas are produced annually on an estimated 1.50 million hectares worldwide [189]. This annual cool-season legume crop is important both economically and ecologically in South Asia and sub-Saharan Africa, and to a lesser degree in North Africa, Central and West Asia, southern Europe, and South America. It is mostly cultivated for feed and fodder in other nations and for consumption in Bangladesh, Nepal, India, Pakistan, and Ethiopia. The crop is also produced to a lesser degree in the Middle East (Syria, Lebanon, Palestine, Iraq, Afghanistan), Northern Africa (Egypt, Morocco, Algeria), China, Chile, and Brazil, as well as many European nations (from southern Germany to Portugal and Spain and east to the Balkans and Russia [40]. The production of grass peas has risen in Bangladesh and Ethiopia but declined in the Mediterranean [190]. This increase in production could be the result of the grass pea's recent popularity as a crop produced in problematic soils. According to Kumar et al. (2021) [189], due to the paucity of research on the genetic and genomic resources available for grass peas in global gene banks, the crop has not made significant strides.

2.3.4.3 Pigeon Pea (Cajanus cajan)

The crop is cultivated on approximately 5.4 million hectares of land worldwide, yielding around 4.49 million tons annually. Approximately eighty-two (82) countries throughout the world cultivate it. India produces over 72% of the world's pigeon peas. In Africa, Malawi, Tanzania, Kenya, Mozambique, and Uganda account for 4% of the world's pigeon pea production. Additionally, the crop is produced in 0.56 million hectares in Eastern and Southern Africa. According to [191], the crop is typically grown alongside other crops, such as cassava, sorghum, millet, and yam. Pigeon pea is mostly grown on about 190.000 hectares of land (3.52% of the world's output land) in Nigeria's northern and southern Guinea savannah agroecological zone.

2.4 Nutritional Value of Neglected Legumes

Today, red meat consumption is the primary source of protein and has surpassed other protein sources, such as legumes, fish, dairy products, poultry, and eggs [54]. This has detrimental effects on both human health and the environment because livestock farming is one of the major contributors to greenhouse gas emissions [55]. By 2050, global consumption of processed foods and animal-source foods must be reduced by more than 50%, while consumption of plant-based foods must increase by more than 100% to facilitate the transition to healthy dietary patterns [56]. The unique nutritional profile of neglected legumes makes them a suitable key candidate for diverse dietary patterns, such as plant-based approaches to human diets. They are considered the most affordable source of nutrients, with an undisputed key role in both human and animal diets. Due to their abundant supply of macro- and micronutrients, they are consumed as dried pulses, sprouts, green leafy vegetables, and as livestock fodder in various parts of the world [58]. Their seeds, particularly Bambara groundnut and marama bean, are used to produce low-fat vegetable yoghurt and vegetable milk, which are comparable to soy milk or dairy milk, and are used in numerous meal preparations to increase protein levels [59,60]. Marama bean seeds are also prepared in various ways, such as roasting, boiling, or grinding, and are used to produce butter and porridge [53].

In comparison to cereal grains, the seeds of neglected legumes are valued as an inexpensive "poor man 's meat," rich in high-quality protein with essential amino acids, carbohydrates, starch, dietary fibre, pectin, sugar components, and oil rich in mono- and di-unsaturated fatty acids and containing no cholesterol [57]. For nutritional composition, the major legumes are comparable (Table 2.2). For example, neglected legumes, including Andean lupin seeds (45%), marama beans (38%), grass pea (34%), and cowpea (32%), have a higher protein content than common beans (25%), groundnut (30%), and chickpea (30.5%). Due to their high oil content, the marama bean and Andean lupin seeds are promising substitutes for oilseed legumes, such as soybeans and groundnuts [22]. Marama beans (43% oil content) have roughly double the oil content of soybeans and groundnuts. Andean lupin has a similar oil content to soybean but is nutritionally superior, as its oil is polyunsaturated and has a high linoleic acid concentration [61,62].

The hyacinth bean is rich in essential amino acids, especially lysine, which is typically low in most cereals [63]. Rice bean is also notably rich in lysine, methionine, tyrosine, valine, tryptophan, vitamins, and minerals (thiamine, niacin, and riboflavin) [64]. Tryptophan and lysine are two essential amino acids abundant in cowpea, which is low in fat but rich in minerals [65-67]. The Bambara groundnut has a considerably greater methionine concentration than several beans. Its protein contains essential amino acids in sufficient quantities to meet the guidelines set by food and agriculture organizations [67]. The nutritional value of rice bean, lupin, Adzuki bean, cowpea, tepary bean, and pigeon pea has been increasingly acknowledged due to their high content of carbohydrates and dietary fiber (Table 2.2). Their starch serves as a primary source of energy in the human diet and contains significant amounts of polysaccharides that have drawn the attention of nutritionists and food technologists.

Table 2.2: Proximate nutritional composition of neglected versus major legumes

				Nutrient Composition (%)				
Neglected Legumes	**Energy (kcal)**	**Protein**	**Fat**	**Carbohydrates**	**Dietary Fiber**	**Ash**	**Price per\kg ($)**	**References**
Tepary bean	158	21.5–25.3	0.9–1.2	47.4–51.5	16.2	4.9–5.0	8.00	[68,69]
Marama bean	525	29.0–38.0	36–43.0	19.0–27.0	16	2.5–3.7	35.20	[53,70]
Horse gram	321	19.0–29.0	0.6–2.6	57.2	5.3	3.0–3.8	15.99	[27]
Bambara groundnut	381	17.4–25.2	6.0–7.9	51.0–70.0	10.0	3.0–5.0	12.55	[71,72]
Andean lupin	370	40.0–45.0	6.0–7.9	51.0–70.0	18.9	3.0–5.0	13.50	[73]
Hyacinth bean	338	23.7–24.9	1.2	54.2–67.2	5.8	3.2–3.5	0.78	[74]
Adzuki bean	294	15.0–29.0	0.4–2.1	40.0–60.0	16.8	2.0–7.0	11.99	[75]
Rice bean	346	18.6–26.0	0.3–2.0	60.7	21.5	3.0–4.3	12.99	[76]
Cowpea	336	20–32	0.6–1.3	50–60	18.2	2.9–3.5	05.40	[77,78]
Moth bean	343	21.9–28.0	1.5	61.5	4.5	3.4	56.00	[79]
Grass pea	348	18–34	1.0–1.6	52.4–59.6	8.3	1.5–2.1	0.73	[80,81]
Pigeon pea	361	19–21.7	1.2–1.3	62.7	15.5	3.9–4.3	17.09	[82]
Major legumes								
Soybean	374	33.0–45.0	19.9	30.2	10.3	3.1	0.52	[6,83]
Common bean	340	16.5–25.2	0.3–1.3	43.5–67.9	4.30	4.2–4.5	2.80	[84,85]

Groundnut	602	26–30	48.0	15.5–16.13	3.0	2.0–2.6	0.68	[86]
Chickpea	343	12.6–30.5	3.8–10.2	52.4–70.9	22.7	2.5–3.2	16.49	[87]
Pea	245	24.4–32.5	0.8–3.9	51.3	13.4	3.1–4.1	16.89	[88]

Neglected legumes also serve as a source of essential minerals, including iron, copper, zinc, sodium, calcium, magnesium, phosphorus, potassium, and manganese (Table 2.3). The iron content of grass pea, Andean lupin, tepary bean, horse gram, and rice bean is higher compared to major legumes including soybean, common bean, groundnut, chickpea, and pea [89,90]. Inclusion of these neglected legumes in the diet has been suggested as a safe alternative to iron supplementation due to their abundance in the iron-rich protein ferritin. Lupin seeds contain the highest level of manganese compared to soybeans, chickpeas, and peas. Bambara groundnut seeds contain a higher zinc content than other neglected legumes and major legumes [91]. This legume is also rich in phosphorus and magnesium compared to other neglected species. In comparison to other legumes like groundnut and pea, the rice bean is particularly rich in calcium and potassium, while horse gram seeds have higher levels of copper than common bean, chickpea, and soybean [92].

Table 2.3: Mineral composition of neglected versus major legumes

	Minerals (mg/100 g) Dry Matter									
Neglected Legumes	**Fe**	**Cu**	**Zn**	**Na**	**Ca**	**Mg**	**P**	**K**	**Mn**	**References**
Tepary bean	12.6	3.7	6.1	34.2	210	281	432	1607	3.6	[93]
Marama bean	4.0	1.0	6.2	64.5	241	274	503	954	1.9	[94]
Horse gram	11.9	5.5	3.4	37.3	105	172	310	415	1.5	[89]
Bambara groundnut	6.7	3.0	19.7	25.2	76	555	563	2200	0.8	[91,95,96]
Andean lupin	16.9	1.3	5.2	20	98	308	249	237	3.8	[97]
Hyacinth bean	3.5	1.3	9.1	43	88	283	395	404	1.6	[98]
Adzuki bean	4.6	0.7	4.1	18.4	65	120	386	1223	1.3	[75]
Rice bean	10.9	4.2	3.1	22.2	274	156	126	2618	2.7	[90]
Cowpea	8.2	0.3	3.9	16	110	184	424	1112	0.2	[99-101]
Moth bean	9.6	1.1	4.4	11.5	120	225	320	2257	1.8	[102]
Grass pea	18.4	0.7	4.4	44.1	200	116	512	644	1.8	[103]
Pigeon pea	4.7	1.8	8.2	12.0	167	127	293	1941	2.4	[104]
Major legumes										
Soybean	8.5	2.4	2.2	27.9	226	236	546	1730	1.2	[105]
Common bean	9.8	1.1	2.3	41.9	183	197	850	2159	2.0	[106]
Groundnut	6.9	2.7	3.4	42	89	210	340	988	2.9	[101]
Chickpea	6.2	2.3	6.2	29.5	114	168	387	1279	1.3	[92]
Pea	5.8	2.4	5.7	93.8	157	110	374	937	1.5	[107]

Neglected legumes, however, form only a minor part of most current human diets, despite the micronutrient deficiencies among rural populations in developing countries that lack the financial means to acquire and consume sufficient quantities of red meat, chicken, fish, fruit, and vegetables [11]. More than 12 million adult deaths have been attributed to poor diets, a 15% increase since 2020. North America and Europe each have the highest percentage of early mortality associated with dietary concerns (31%), whereas Africa has the lowest rate (17%) but is still considerable [108]. Only 1.1% of the world's overall food supply and 1.3% of the world's total vegetable food supply come from legumes, which is relatively low. Hence, there is a need to supplement diets with poor nutritional value by including neglected legumes.

The global nutrition report indicates that the global nutrition targets will not be achieved by 2025 [109]. For the past two years, there has been a substantial increase in the number of undernourished people, and by 2021, up to 828 million people were hungry worldwide. The frequency of undernourishment increased from 8% in 2019 to approximately 9.3% in 2020 and then to 9.8% in 2021. The number of hungry people in Africa continues to rise [110]. As of 2020, over one-third of the continent's population was undernourished. In Africa, 282 million people experience hunger, which is more than double the number in any other region globally. Conditions are deteriorating across East Africa, where 7.2 million people are at risk of starvation, and another 33.8 million face acute food insecurity. Around 12.8 million children are acutely malnourished. In this regard, it is necessary to focus attention on the nutritional profiling of various neglected legumes to enhance their value chain, utilization, and production of affordable and innovative value-added products, thereby alleviating food and nutritional insecurity.

2.5 Utilization of Neglected Legumes

Although neglected legumes could produce better food products, more naturally balanced diets, improved pharmaceutical products, natural pesticides and flavourings, dyes, and beverages, numerous food legumes are still underutilized [111]. However, the seeds are rich in vitamin A, leucine, and lysine. They can be eaten fresh, fried, boiled, tinned, frozen, baked, dried, or roasted; they are typically cooked before eating [112,113]. Dishes include salads, casseroles, soups, and stews. Vegetables are made from both immature and mature pods. Mature seed flour is used in other recipes and combined with oil or butter to make porridge. Bambara groundnut is also canned. Additionally, the haulm can be used for animal feed. According to [111], the processing and marketing status have been recorded. Horse gram seeds are fermented to produce a sauce similar to soy sauce. Mature, dry seeds of neglected legumes can be used as a pulse or combined with other ingredients to prepare meals; their flour can be used as a bean paste or mixed with bread flour to produce noodles. Immature pods from the Bambara groundnut are used in soup, and the immature seeds are typically consumed raw, cooked, or grilled. Like many other underutilized legumes, rice beans are a versatile and multipurpose species. Asia uses immature pods and leaves as vegetables and pulse. Soups and stews are also cooked with the seed. Neglected legumes could also be consumed with cereals, tubers, roots, and other crops [114,115]. They can be used with grains, such as sorghum, to make bread [116]; they can also be combined with maize to produce a blend extrudate, which can then be converted into flour [117]. Ref [118] suggests using lime beans as a thickening agent in soups to make biscuits.

2.6 Health Benefits of Consuming Neglected Legumes

Good health is undoubtedly a universal concern and the desire of every human being. Including neglected legumes in the daily diet has many beneficial physiological effects in controlling and preventing various metabolic diseases such as diabetes mellitus, coronary heart disease, and colon cancer [83]. The role of legumes as therapeutic agents in the diets of people suffering from metabolic disorders is currently gaining interest. They produce a wide range of secondary metabolites, which serve as their chemical armory for defense against predators [119]. The variability in these secondary metabolites allows the classification of genera and subgenera based on chemical taxonomy. Those metabolites include anti-nutrients such as inhibitors of digestion and compounds that interfere with human metabolism, reaching as far as brain function and hormonal control. Some of these metabolites are beneficial because they inhibit the growth of cancer cells or enhance their antioxidant activity, which can delay ageing in humans [119,120].

The low glycaemic index and high content of undigestible fibres in neglected legumes (e.g., Bambara groundnut, pinto, navy, kidney, lima, and black beans) aid in glycaemic control in diabetic individuals, contributing to the prevention of insulin resistance, which represents the prodrome of type 2 diabetes [121]. High-soluble dietary fiber lowers cholesterol levels by raising the ratio of bile acid to salt excretion in the feces and supplying colonic bacteria with a substrate converted to short-chain fatty acids anaerobically in the intestine (acetate, propionate, and butyrate) [122]. Butyrate inhibits histone deacetylase, leading to changes in gene expression that affect cancer cell proliferation, differentiation, and apoptosis [57,123].

Consuming legumes is also associated with a reduced breast and prostate cancer risk [124]. For example, lectin toxins and other compounds from the tepary bean are helpful in cancer chemotherapy [125]. Due to the presence of two distinct types of bioactive proteins, each with a unique impact on cancer cells, this previously neglected legume is ten times more effective than chemotherapy in treating cancer [125]. The amino acid l-homoarginine present in grass pea provides benefits in overcoming the consequences of hypoxia, the inadequate oxygen supply at the tissue level associated with cancer tumor development [81]. Other effective cancer-fighting agents in neglected legumes include bioactive phytochemicals (saponins, phytic acid, and polyphenols) and micronutrients like folate and selenium. Folate also lowers the chance of neural tube abnormalities like spina bifida in newborns [126].

Micronutrients present in neglected legumes play a vital role in bone health and teeth (calcium), protein synthesis, antioxidative activity, plasma membrane stabilization (zinc), enzyme activity, iron metabolism, and hemoglobin production (copper), and prevention of anemia (iron), carbohydrate and lipid metabolism (zinc, chromium), Potassium and magnesium control blood pressure and are excellent at slowing down natural aging processes [127]. Neglected legumes, such as adzuki beans, horse gram, moth beans, and hyacinth beans, are used in traditional medicines from many parts of the world to treat various ailments, including dropsy, cough, bronchitis, cardiopathy, liver problems, and inflammation [128]. Moth bean also treats fever and irregular menstrual cycles in women [129], supports gut health, boosts the immune system [130], repairs muscle, promotes regular bowel movements, and is suitable for renal diseases due to its properties as an astringent, diuretic, and tonic. Its roots are narcotic in nature [129]. Neglected legumes further contribute to a longer lifespan and improved mental wellness. Their regular consumption enhances satiety, reduces stress, anxiety, and sadness in older individuals, and encourages weight loss by reducing adipose tissue accumulation [131]. However, despite these health benefits, their actual intake remains low.

Isoflavones found in underutilized legumes, such as cowpea, adzuki beans, and mung beans, prevent bone loss in postmenopausal women [132]. This includes anthocyanins, which trigger adipocytes to release adiponectin, a cardioprotective hormone with anti-inflammatory properties in blood vessel cells linked to a lower risk of heart attack in men and women [133]. Flavonoids are the most common bioactive compounds of neglected legumes, especially those with colored seed coats, and are the main class of polyphenols showing the highest antioxidant potential. This group encompasses pro-anthocyanins and anthoxanthins; they also exhibit free radical scavenging capacity, are anti-inflammatory, and positively impact the immune response [134].

Under stress conditions, neglected legumes produce several bioactive compounds for survival [135]. The bioactive compounds, along with carbohydrates (including slow-release and indigestible types), lipids (such as polyunsaturated fatty acids), and dietary fibre (both soluble and insoluble), exert beneficial therapeutic effects on human health. Researchers have isolated and identified several bioactive compounds with potential nutraceutical properties (Table 2.4). Due to the presence of bioactive compounds, neglected legumes possess nutraceutical values and have vast potential to serve as raw materials for pharmaceutical companies. The isolation and extraction of bioactive compounds from edible and non-edible plant parts, including the seed coat, can be applied to manufacture potent natural antioxidants in the nutraceutical industry. However, several health benefits of underutilized legumes remain to be ascertained and validated through the characterization of plant extracts, their identification, and the isolation of related bioactive compounds.

Table 2.4: Health benefits of bioactive compounds found in neglected legumes

Neglected Legumes	Bioactive Compounds	Health Benefits	References
	Phenolic acids		
Marama bean, rice bean, Bambara groundnut	Caffeic acid	Antioxidant, Antidiabetic, Neuroprotective, Anti-carcinogenic, Anti-inflammatory	[136,137]
Andean lupin, moth bean, pigeon pea, cowpea	Gallic acid	Anti-inflammatory, Antineoplastic, Antioxidant	[138-141]
Adzuki bean, mung bean	Vanillic acid	Cardioprotective, Antiapoptotic, Antioxidant, Neuroprotective, Hepatoprotective	[142,143]
Marama bean	Protocatechuic acid	Antidiabetic, Anti-carcinogenic, Antioxidant, Neuroprotective, Anti-atherosclerosis	[144]
Adzuki bean	Syringic acid	Neuroprotective, Antioxidant, Anti-inflammatory, Anti-microbial, Hepatoprotective	[145]
Grass pea, horse gram	p-Hydroxy Benzoic acid	Antiviral, Nematocidal, Anti-inflammatory, Antimutagenic, Hypoglycaemic, Antioxidant	[146,147]
Cowpea, Adzuki bean	p-Coumaric acid	Anti-microbial	[22]
Bambara groundnut, rice bean	Ferulic acid	Antidiabetic, Anti-carcinogenic, Neuroprotective, Antioxidant	[148]
Rice bean, black bean	Sinapic acid	Anti-bacterial, Antioxidant, Anti-carcinogenic, Neuroprotective, Anti-glycaemic	[22]
	Flavonoids		
Bambara groundnut, moth bean	Rutin	Antiarthritic, Analgesic, Antidiabetic, Cytoprotective, Neuroprotective, Anti-carcinogenic	[149,150]
Andean lupin	Myricetin	Antidiabetic, Analgesic, Anti-carcinogenic, Anti-microbial, Anti-hypertensive, Anti-mutagenic	[22]
Andean lupin, cowpea, Adzuki bean	Catechin	Anti-obesity, Anti-carcinogenic, Antidiabetic, Antioxidant, Neuroprotective, Hepatoprotective	[151]
Moth bean, pigeon pea	Hesperidin	Antioxidant, Anti-inflammatory	[22,152]

Bambara groundnut	Kaempferol	Anti-inflammatory, Anti-carcinogenic, Antioxidant	[22,153]
Bambara groundnut	Quercetin	Antiviral, Anti-carcinogenic, Anti-inflammatory	[22,154]
Marama bean	Phytosterols	Lower blood cholesterol levels	[155]
Bambara groundnut, pigeon pea	Saponins	Lower blood cholesterol and glucose level, Anti-carcinogenic, Immune-stimulatory activity	[156-158]
Adzuki bean, cowpea, mung bean	Carotenoids	Eye protective, Anti-carcinogenic, Antioxidant	[22,147,159]

2.7 Nutraceutical Properties of Neglected Legumes and Their Impact on Human Health

Neglected legume seeds are considered influential nutraceuticals due to their positive impact on human health, which can help prevent or treat diseases such as diabetes, cancer, digestive tract disorders, cardiovascular disease, and obesity [160]. They contain phytochemicals that are essential to human metabolism in individuals who frequently consume neglected legumes [160]. Consuming phytochemicals through a balanced diet may have health benefits by warding off a host of illnesses and disorders, including inflammation and high blood pressure. Saponins, in particular, play a key role as anti-cancer agents by limiting the development of carcinogenic substances in the colon. Additionally, they may have immune-stimulating effects by promoting the production of cytokines, such as interleukins and interferons. Saponins may also have several additional advantageous effects, including immunomodulatory, anti-hypercholesterolemic, anti-hypoglycemic, anti-inflammatory, anti-fungal, and anti-parasitic properties. The antioxidant content pre-sent in neglected legumes is important in the treatment of numerous illnesses, such as schizophrenia, autoimmune disorders, different respiratory diseases, and ocular disorders [162]. For instance, adding burned pigeon pea seeds to coffee can help alleviate vertigo and migraines, while fresh seeds can aid in treating male urinary incontinence. On the other hand, kidney diseases are treated using immature seeds. The husks from pigeon pea seeds have strong antioxidant and anti-hyperglycemic properties, making them a possible organic source for nutraceuticals designed to treat hyperglycemia [163].

Neglected legume seeds also contain phytic acid, an antinutrient. It is kept in the endosperm of legume seeds as phosphate. Phytic acid functions as an anti-HIV agent by preventing the viral genome from being transcribed. Kidney stones are prevented from forming by phytic acid, which reduces the solubility of calcium, fluoride, and phosphate and shields them from demineralization. It also aids in the prevention of cavities, plaque, and tartar in the teeth by chelating iron, suppressing iron-related initiation, and promoting carcinogenesis. Phytic acid also lowers the risk of colon cancer. Furthermore, due to its ability to enhance natural killer cell activity, which is associated with reduced tumour incidence, it may have potential therapeutic utility in cancer [164]. Canavalia cathartica's lectin, Concanavalin C is used as a tissue marker, immuno-modulator, and blood grouping agent [164,165]. Tumor cells are destroyed in the liver as a result of the immune cell responses that Concanavalin A triggers. Concanavalin A exhibits both autophagic and anti-hepatomic (immunomodulatory) activities after attaching to the mannose moiety. According to [166], phytosterols are important regulators of metabolism and cholesterol transport, influencing the expression of liver genes, and they also impact intestinal genes through transcription factors.

2.8 Potential Anti-Nutritional Factors Present in Neglected Legumes

Neglected legume seeds have potential nutritional and health-promoting benefits. However, they also contain anti-nutritional elements, which may be harmful when eaten raw but, when processed and treated, may be beneficial to human health [160]. The existence of antinutritional substances restricts their biological value and suitability as food. Researchers suggest that neglected legumes can trigger allergic reactions when consumed due to primary sensitization or cross-reactions with other legumes, which is also a serious problem [160]. For example, underutilized legumes such as Andean lupin have several antinutritional properties that can be either protein- or non-protein-based [167]. Neglected legume seeds include a variety of ubiquitarian and specialized anti-nutritional components, including lectins, phytates, proteinase inhibitors, and polyphenols [168]. Antinutrients in neglected legume seeds are reported to restrict the amount of protein and carbohydrates that may be used. According to [169], the anti-nutritional components are rendered inactive by high processing temperatures; therefore, these adverse effects are only noticeable after consuming raw and unprocessed seeds or flour.

Most of the anti-nutritional factors associated with neglected legumes affect the digestive system. These factors include blocking digestive enzymes (such as protease inhibitors), lectins that impair hydrolytic functions and transport at the enterocyte site, phytates and polyphenols that form insoluble complexes, and α-galactosides that increase gas production in the colon [167]. Trypsin inhibitors of the Kunitz and Bowman-Birk types, as well as α-amylase inhibitors such as those found in Adzuki beans, are the most well-known and frequently occurring protein inhibitors in legume seeds [170]. Additionally, phenolic chemicals, saponins, alkaloids, phytates, and other non-protein anti-nutritional substances found in neglected legume seeds hinder the biological uptake of these nutrients [160]. To increase the utilization of neglected legumes, several methods and mechanisms of action are employed to mitigate the effects of antinutrient factors (Table 2.5). Genetic manipulation (selection from natural or artificial diversity, genetic engineering of biosynthetic pathways, or modification of the toxic protein itself), post-harvest processing (such as germination, boiling, leaching, fermentation, or extraction), or the selection of plant genotypes with low levels of these factors can all help achieve this reduction. Other methods include improving tolerance to antinutrient factors and supplementing diets with protective factors such as methionine, threonine, and feed enzymes.

Table 2.5: Antinutrients present in neglected legumes, processing methods, and mechanisms of action.

Neglected Legumes	Antinutrient	Processing Method	Mechanism of Action	References
Marama bean	Phytic acid, Polyphenols, Trypsin inhibitors, Lectins	Soaking, Germination, Fermentation, Boiling, Steaming, Heat treatment	Breaks down phytic acid, increasing bioavailability of minerals such as zinc, iron, and calcium, Breaks down polyphenols, reducing their binding to proteins and minerals Inactivates trypsin inhibitors, increasing protein digestibility	(Bower et al., 1998) [192]
Bambara groundnut	Phytic acid, Polyphenols	Soaking, Germination, Fermentation	Breaks down phytic acid and polyphenols, increasing bioavailability of minerals	(Musah et al., 2021) [96]
Rice bean	α-Galactosides, Oxalates, Saponins	Soaking, Germination, Fermentation, Boiling, Steaming	Breaks down α-galactosides, reducing gas production and improving digestibility Breaks down oxalates, reducing their binding to minerals such as calcium and magnesium Breaks down saponins, reducing their binding to cholesterol and increasing nutrient absorption	(Sharma et al., 2023)
Grasspea	ODAP (β-N-Oxalyl-L-α,β-diaminopropionic acid)	Soaking, Boiling, Autoclaving	Breaks down ODAP, reducing neurotoxicity	(Hillocks and Maruthi, 2012)

Pigeon pea, cowpea, Mung bean	Phytic acid, Polyphenols	Soaking, Boiling, Fermentation	Breaks down phytic acid and polyphenols, increasing bioavailability of minerals	(Gomezulu and Mongi, 2022; Gonçalves et al., 2016)
Jack bean, Lima bean, African yam bean	Phytic acid, Polyphenols, Lectins	Soaking, Boiling, Fermentation	Breaks down phytic acid, polyphenols, and lectins, increasing bioavailability of minerals	(Akande, 2016; Farinde et al., 2018; Adegboyega et al., 2020)
Andean lupin	Alkaloids, Phytic acid, Polyphenols	Soaking, Boiling, Autoclaving	Breaks down alkaloids, reducing toxicity, Breaks down phytic acid, increasing bioavailability of minerals	(Romero-Espinoza et al., 2020
Adzuki bean	Raffinose, Phytic acid, Trypsin inhibitors, Polyphenols	Soaking, Germination, Fermentation, Heat treatment	Breaks down raffinose, reducing gas production and improving digestibility, Breaks down phytic acid, increasing bioavailability of minerals	(Sharma et al., 2019)
Horse gram	Flavonoids, Trypsin inhibitors, Polyphenols, Phytic acid	Boiling, Steaming, Fermentation, Soaking, Germination, Fermentation	Breaks down flavonoids, reducing their binding to proteins and minerals Inactivates trypsin inhibitors, increasing protein digestibility	(Rizvi et al., 2022)
Moth bean	Protease inhibitors, Amylase inhibitors, Saponins, Oxalates, α-Galactosides	Heat treatment, Autoclaving	Inactivates protease inhibitors, increasing protein digestibility Inactivates amylase inhibitors, increasing carbohydrate digestibility	(Bhadkaria et. al, 2022)

2.9 Role of Neglected Legumes in Food Security and Sustainable Agriculture

It is projected that by 2025, the global population will reach 8.1 billion. This number will rise to 9.6 billion by 2050 and 10.9 billion by 2100 [171]. The imbalance in food production brought on by climate change could lead to a future food insecurity crisis because of the growing global population [172]. Malnutrition, a physiological condition caused by undernourishment or poor absorption or utilization of ingested nutrients due to certain pathological conditions, must be prevented through the adoption of alternative and sustainable food sources. African countries depend on staple cereal foods to sustain their diets, consuming only one type of carbohydrate, such as rice or maize, while lacking a significant source of protein [173]. As a result, protein-energy deficiency is a significant issue in developing countries [99]. Sustainable protein sources are needed to meet the enormous rise in protein demand that the world's population growth will bring about. Reintroducing neglected legumes to the diet as a promising intervention to address the world's food and nutrition concerns will significantly improve human nutrition and food security and reduce the risk of over-reliance on minimally significant crops. Consumers highly accept proteins from neglected legumes. They are abundant, sustainable, and not allergenic. Moreover, they can be utilized as functional additives to enhance the nutritional value of processed meals and contribute to the development of nutrient-dense, economically viable, and sustainable diets [174].

The sustainability of agricultural production systems has become increasingly crucial for enhancing food security in the years to come. This is due to critical challenges, including arable land degradation, nutrient deficiencies, and uncertainties related to climate change. Neglected legumes are crucial to this concern, as they provide a wide range of benefits while adhering to sustainability standards [175]. Their intensification into cropping systems could provide various benefits to the ecosystem by reducing the excessive use of external inputs (i.e., fertilizers and agrochemicals), improving soil structure, increasing organic carbon concentrations, enhancing soil health, quality, and fertility, while also increasing production and empowering local communities.

Soil fertility has emerged as one of the most significant biophysical constraints to increasing agricultural production, posing a threat to food security [176]. Smallholder farmers in marginal environments require additional financial resources to purchase sufficient mineral fertilizers to replenish the soil nutrients lost through harvested crop products. However, neglected legumes have the potential to effectively transfer fixed nitrogen to coexisting crops while reducing fertilizer costs [177]. It is fundamental to promote crop diversification of neglected legumes with high yield potential and nutritional value. Growing a diversity of neglected legumes is essential for improving nationwide nutrition, striving towards 100% food security, and increasing farmers' economic returns. When used as rotation crops, they help resource-poor smallholder farmers improve their financial status [178]. Their intensification in intercropping systems could improve yields, ensure production stability, increase scale efficiency, and provide insurance because farmers can still rely on the other crop if one fails. Neglected legumes are less susceptible to weeds, diseases, and pests than cereal crops. For instance, rice beans, tepary beans, adzuki beans, and horse gram have been observed to be immune to several pests and diseases. They break the life cycle of problematic pests, lowering the number and severity of pests in succeeding crops [179]. Therefore, farmers may reduce their reliance on pesticides and herbicides in subsequent crops because of the break-crop effect. Furthermore, introducing these legumes into agricultural rotation programs will help re-duce greenhouse gas emissions and address the associated economic and environmental challenges.

2.10 Economic and Environmental Trade-Offs Between Neglected Legumes and Major Legumes

The economic and environmental trade-offs between neglected legumes and major legumes are complex and multifaceted. While major legumes, such as soybeans and common beans, generally offer higher economic returns and are supported by well-developed value chains, they have been associated with environmental challenges, including input intensification. However, improved management practices have demonstrated that their production can also be made more sustainable. Neglected legumes, on the other hand, provide ecosystem services, promote biodiversity, and offer climate resilience but face economic challenges due to limited market demand and underdeveloped value chains. To promote sustainable agriculture and food systems, it is essential to promote the production and consumption of both neglected and major legumes. This can be achieved through developing markets for neglected legumes to increase their economic viability; investing in the development of neglected legume value chains to improve efficiency and reduce transaction costs; promoting sustainable agriculture practices, such as agroecology and regenerative agriculture, to reduce the environmental impacts of major legume cultivation; and conducting research and development to improve the productivity, disease resistance, and climate resilience of both neglected and major legumes. Adopting a holistic approach that considers both economic and environmental-related factors could promote the sustainable consumption of neglected legumes, ensuring food security, environmental sustainability, and equitable economic development.

2.11 Adaptation of Neglected Legumes to Climate Change

Global food security is currently threatened by climate change [180]. It is projected to negatively impact crop yields, leading to a 25% decline by 2050 [181]. Inconsistent or poor yields have extensive consequences, as they result in less food for the household and reduced revenue for other essential items. Yield stability is crucial in ensuring food security, and for a household to be considered food secure, it must have regular access to adequate food with high nutritive value [182]. The struggle to attain food security is due to farmers' reliance on rainfall, which is often accompanied by drought, low humidity, high temperatures, and increased agricultural risks. These significant concerns continue to threaten households' food security status [183]. Inclusion of neglected legumes, particularly in developing nations, could be crucial in tackling food and nutritional insecurity in the context of climate change due to their drought-tolerance characteristics, increased resilience against climate change, ability to increase crop yield under adverse conditions where other crops would fail, and the potential to support agricultural productivity on poor soils [184].

Hyacinth bean, tepary bean, cowpea, and adzuki bean are well-adapted to poor soils, salinity, acidity-alkalinity, and heavy metal stress [22]. Their tolerance involves a series of morphological, physiological, and biochemical changes that facilitate better adaptation. The adaptive mechanisms that enable them to survive and produce under extreme soil and agroclimatic conditions could be useful in low- and erratic-rainfall regions [22]. Their deep root system development and distribution enable more efficient extraction of available water from the deep levels of the soil profile [185]. Such adaptations result in more efficient water uptake; consequently, neglected legumes possess the intrinsic ability to enhance water use efficiency and conserve natural resources. Their inclusion will enable vulnerable, resource-poor farmers to adapt to changing climatic conditions, improve long-term resource use efficiency, ensure yield stability, and alleviate food and nutrition insecurity, particularly in marginal environments.

2.12 Challenges to Mainstream Utilization of Neglected Legumes

Neglected legumes have received minor attention from researchers, plant breeders, growers, policymakers, traders, technology providers, and consumers due to agronomic, genetic, economic, and social factors [186]. As a result, they do not currently play a significant role in mitigating food and nutrition insecurity due to a lack of focused research and the use of unimproved cultivars, which have resulted in a lack of quality seeds and consequently low yields [22]. Over the past decades, these legumes have been primarily produced by vulnerable and marginalized groups with limited skills and technology to produce and process them into nutritious food products [34]. They are grown as secondary crops, intercropped with cereals, and occasionally used as rotational crops with cereals, which has resulted in stagnant production over the years in most developing countries. Lack of knowledge about the cultivation of neglected legumes and their use and nutritional value are other reasons for the gap in legume production [36,37]. Additionally, nutrition policies have not effectively focused on raising awareness among people about the importance of dietary diversity and the inclusion of neglected legumes in their diets. Hence, the high demand for cereals has pushed legume production to marginal environments characterized by low rainfall and poor soils, a characteristic of most smallholder and communal farming systems.

Several socio-economic challenges faced by smallholder farmers contribute to the underutilization of neglected legumes. Smallholder farmers are highly vulnerable to climate change and environmental degradation, which lead to crop failures, reduced yields, and decreased incomes; have limited access to markets and market knowledge, making it challenging to sell their produce at competitive prices; have limited access to credit and financial services, which limits the investment in farms or management of risks; and have limited access to technology and extension services, which makes it challenging to adopt new technologies and crops and improve farming practices. Moreover, smallholder farmers, particularly women and marginalized groups, face social inequality and land rights issues, which limit access to land, credit, and other resources. Ageing is another factor limiting the production of neglected legumes, resulting from the limited involvement of youth in agriculture, which leads to a lack of innovation and modernisation in farming practices. Promoting climate-resilient agricultural practices to enhance the sustainability of neglected legume production can be achieved by providing extension services and technology transfer to smallholder farmers, establishing market linkages, and providing market information. This approach also supports the participation of women and marginalised groups in agriculture, promotes social inclusion and empowerment through training and capacity building, and fosters the development of market linkages.

2.13 Potential Strategies to Resolve Underutilization of Neglected Legumes

A tremendous research effort, combined with the development of value chains for neglected legumes, could provide some impetus to challenge the dominance of major legumes [184]. Participatory action research can serve as an entry point to empower communities in developing countries, particularly vulnerable, resource-poor farmers, by providing opportunities to co-learn and experiment with these neglected legumes [187]. The awareness and traditional knowledge of these legumes regarding their utility and cultivation need to be elevated from a basic farmers' level to a broad spectrum of scientific practices. This will lead to the adoption and utilization of these climate-smart, neglected legumes, and enhance the implementation of appropriate management approaches to promote sustainable food production. Secondly, advancements in speed breeding, genetic improvement for developing desirable traits, enhanced yield, and selecting elite attributes are essential across different climate-resilient crop-ping systems [188]. Therefore, intensive future research must focus on integrating the traits of these legumes into greater production, which could elevate their economic status in the global market. This will significantly increase intake and, consequently, contribute to the mitigation of current health and environment-related global crises, including food and nutrition insecurity.

Food and nutrition security projects should explore and encourage amendments to testing, importing, and exporting regulations about legume varieties that are not locally produced to make them more accessible to South African markets, particularly at the local level. Although there have been reports detailing the potential of neglected legumes, few have provided a roadmap for exploiting this potential [109]. Thus, there is a need to identify high-potential, neglected legumes, prioritise them, and articulate a strategy with actionable recommendations for exploiting the potential of these legumes. The development of the strategy should address the challenges and obstacles, including but not limited to micronutrient deficiency, the unbearable burden of malnutrition, hidden hunger, and the opportunities or benefits brought by neglected legume utilisation. A guiding framework for addressing the challenges of food and nutritional insecurity should outline coherent actions and activities for future research and development funding on neglected legumes. Lastly, the policies should not be limited to altering food consumption habits and incorporating neglected legumes into the diet to combat malnutrition, major chronic diseases, and associated risk factors.

2.14 Conclusion

The importance of neglected legumes in current and future agriculture cannot be understated. They form a minor part of everyday human diets despite their potential to provide a sustainable solution to food and nutritional insecurity, malnutrition, hunger, and their increasingly significant role in improving human health worldwide. Sub-Saharan Africa’s food nutritional security requires a major refocus on neglected legume identification, accompanied by intensive research on genetic improvement and development to enhance climate-resilient cultivars with improved grain characteristics. Future research on genetic improvement and development should encompass establishing breeding programs to improve the yield, disease resistance, and nutritional quality of neglected legumes; the development of genetic markers associated with desirable traits to facilitate marker-assisted selection and breeding; the application of genomic selection to accelerate the breeding process and improve the accuracy of selection; and the utilization of mutant breeding techniques to induce genetic variation and improve the desirable traits of neglected legumes. Raising awareness and educating farmers, consumers, and policymakers about the neglected legume value and advocating for better utilization in crop rotations while addressing challenges in trade will significantly increase their production over the coming decades and utilization throughout the food system.

As climate change manipulates the environmental and socio-economic drivers of food security, the time has come to rethink and orient policies to sustain neglected legume production and achieve long-term benefits for all communities across the globe. There is a need to promote the cultivation of neglected legumes to sustain food security, especially in the developing countries of sub-Saharan Africa. The policies should not be limited to altering food consumption habits and including neglected legumes in the diet to fight against malnutrition, major chronic diseases, and associated risk factors. Encouragement of neglected legumes' integration into cropping systems and the implementation of specific programs to assist smallholder farmers who are highly vulnerable to climate change could be smart climate adaptation strategies. This will aid in establishing agricultural systems that are resilient and cost-effective with an enormous capacity to improve household livelihoods, nutrition, and food security. Moreover, there is a need for market development and value chains for neglected legumes to improve their availability and accessibility; funding provision for research on neglected legumes to address the knowledge gaps and improve their productivity and utilization; strengthening of extension services to disseminate information and technologies to farmers and consumers on the production and utilization of neglected legumes; incorporation of neglected legumes into school meals and food assistance programs to improve nutrition and promote their consumption; engaging the private sector in the production, processing, and marketing of neglected legumes to improve their availability and accessibility; fostering international cooperation to share knowledge, technologies, and best practices in the production and utilization of neglected legumes.

References

1. Adesogan, A.T.; Havelaar, A.H.; McKune, S.L.; Eilittä, M.; Dahl, G.E. Animal source foods: Sustainability problem or malnutrition and sustainability solution? Perspective matters. Glob. Food Secur. 2020, 25, 100325.

2. Geremew, K.; Yitayih, M.; Alemayehu, T.; Dessie, T. Overview on the impacts of nutrition-sensitive intervention on dietary diversity and nutritional status of women and children in developing countries. Ethiop. J. Public Health Nutr. 2020, 4, 78–85.

3. WHO. The State of Food Security and Nutrition in the World 2021: Transforming Food Systems for Food Security, Improved Nutrition and Affordable Healthy Diets for All; Food & Agriculture Organization: Rome, Italy, 2021; Volume 2021.

4. Mozaffarian, D.; Angell, S.Y.; Lang, T.; Rivera, J.A. Role of government policy in nutrition—Barriers to and opportunities for healthier eating. BMJ 2018, 361, k2426.

5. Paliwal, R.; Adegboyega, T.T.; Abberton, M.; Faloye, B.; Oyatomi, O. Potential of genomics for the improvement of underutilized legumes in sub-Saharan Africa. Legume Sci. 2021, 3, e69.

6. Cullis, C.; Kunert, K.J. Unlocking the potential of orphan legumes. J. Exp. Bot. 2017, 68, 1895–1903.

7. Popoola, J.; Ojuederie, O.; Omonhinmin, C.; Adegbite, A. Neglected and underutilized legume crops: Improvement and future prospects. In Recent Advances in Grain Crops Research; IntechOpen: London, UK, 2019.

8. Mabhaudhi, T.; Chimonyo, V.G.; Modi, A.T. Status of underutilised crops in South Africa: Opportunities for developing research capacity. Sustainability 2017, 9, 1569.

9. Conti, M.V.; Guzzetti, L.; Panzeri, D.; De Giuseppe, R.; Coccetti, P.; Labra, M.; Cena, H. Bioactive compounds in legumes: Implications for sustainable nutrition and health in the elderly population. Trends Food Sci. Technol. 2021, 117, 139–147.

10. Medendorp, J.; DeYoung, D.; Thiagarajan, D.G.; Duckworth, R.; Pittendrigh, B. A systems perspective of the role of dry beans and pulses in the future of global food security: Opportunities and challenges. In Dry Beans and Pulses: Production, Processing, and Nutrition; John Wiley & Sons: Hoboken, NJ, USA, 2022; pp. 531–550.

11. Foyer, C.H.; Lam, H.-M.; Nguyen, H.T.; Siddique, K.H.; Varshney, R.K.; Colmer, T.D.; Cowling, W.; Bramley, H.; Mori, T.A.; Hodgson, J.M. Neglecting legumes has compromised human health and sustainable food production. Nat. Plants 2016, 2, 16112.

12. Kumar, J.; Kumar, A.; Sen Gupta, D.; Kumar, S.; DePauw, R.M. Reverse genetic approaches for breeding nutrient-rich and climate-resilient cereal and food legume crops. Heredity 2022, 128, 473–496.

13. Mefleh, M.; Pasqualone, A.; Caponio, F.; Faccia, M. Legumes as basic ingredients in the production of dairy-free cheese alternatives: A review. J. Sci. Food Agric. 2022, 102, 8–18.

14. Yuvaraj, M.; Pandiyan, M.; Gayathri, P. Role of legumes in improving soil fertility status. In Legume Crops-Prospects, Production and Uses; BoD–Books on Demand: Norderstedt, Germany, 2020; pp. 1–8.

15. Kebede, E.; Bekeko, Z. Expounding the production and importance of cowpea (Vigna unguiculata (L.) Walp.) in Ethiopia. Cogent Food Agric. 2020, 6, 1769805.

16. Chandra, M.S.; Naresh, R.; Thenua, O.; Singh, R.; Geethanjali, D. Improving resource conservation, productivity and profitability of neglected and underutilized crops in the breadbasket of India: A review. Breed. Sci. 2020, 70, 19–31.

17. Sita, K.; Kumar, V. Role of Gamma Amino Butyric Acid (GABA) against abiotic stress tolerance in legumes: A review. Plant Physiol. Rep. 2020, 25, 654–663.

18. Ebert, A.W. Potential of underutilized traditional vegetables and legume crops to contribute to food and nutritional security, income and more sustainable production systems. Sustainability 2014, 6, 319–335.

19. Mayes, S.; Massawe, F.; Alderson, P.; Roberts, J.; Azam-Ali, S.; Hermann, M. The potential for underutilized crops to improve security of food production. J. Exp. Bot. 2012, 63, 1075–1079.

20. Padulosi, S.; Thompson, J.; Rudebjer, P. Fighting Poverty, Hunger and Malnutrition with Neglected and Underutilized Species: Needs, Challenges and the Way Forward; Bioversity International: Rome, Italy, 2013; 60p.

21. Mohanty, C.S.; Singh, V.; Chapman, M.A. Winged bean: An underutilized tropical legume on the path of improvement, to help mitigate food and nutrition security. Sci. Hortic. 2020, 260, 108789.

22. Chongtham, S.K.; Devi, E.L.; Samantara, K.; Yasin, J.K.; Wani, S.H.; Mukherjee, S.; Razzaq, A.; Bhupenchandra, I.; Jat, A.L.; Singh, L.K. Orphan legumes: Harnessing their potential for food, nutritional and health security through genetic approaches. Planta 2022, 256, 24.

23. Rao, I.; Beebe, S.; Polania, J.; Ricaurte, J.; Cajiao, C.; Garcia, R.; Rivera, M. Can tepary bean be a model for improvement of drought resistance in common bean? Afr. Crop Sci. J. 2013, 21, 265–281.

24. Blair, M.W.; Pantoja, W.; Carmenza Muñoz, L. First use of microsatellite markers in a large collection of cultivated and wild accessions of tepary bean (*Phaseolus acutifolius*). Theor. Appl. Genet. 2012, 125, 1137–1147.

25. Jackson, J.C.; Duodu, K.G.; Holse, M.; de Faria, M.D.L.; Jordaan, D.; Chingwaru, W.; Hansen, A.; Cencic, A.; Kandawa-Schultz, M.; Mpotokwane, S.M. The morama bean (*Tylosema esculentum*): A potential crop for southern Africa. Adv. Food Nutr. Res. 2010, 61, 187–246.

26.Chimwamurombe, P.M. Domestication of [*Tylosema esculentum* (Burchell) Schreiber] (Marama bean): A work in progress in Namibia. Biosci. Biotechnol. Res. Asia 2016, 8, 549–556.

27. Aditya, J.; Bhartiya, A.; Chahota, R.K.; Joshi, D.; Chandra, N.; Kant, L.; Pattanayak, A. Ancient orphan legume horse gram: A potential food and forage crop of future. Planta 2019, 250, 891–909.

28. Dikshit, N.; Katna, G.; Mohanty, C.S.; Das, A.B.; Sivaraj, N. Horse gram. In Broadening the Genetic Base of Grain Legumes; Springer: Berlin/Heidelberg, Germany, 2014; pp. 209–215.

29. Soumare, A.; Diedhiou, A.G.; Kane, A. Bambara groundnut: A neglected and underutilized climate-resilient crop with great potential to alleviate food insecurity in sub-Saharan Africa. J. Crop Improv. 2022, 36, 747–767.

30. Redjeki, E.S.; Ho, W.; Shah, N.; Molosiwa, O.; Ardiarini, N.; Kuswanto, N.R.A.; Mayes, S. Understanding the genetic relationships between Indonesian bambara groundnut landraces and investigating their origins. Genome 2020, 63, 319–327.

31. Berru, L.B.; Glorio-Paulet, P.; Basso, C.; Scarafoni, A.; Camarena, F.; Hidalgo, A.; Brandolini, A. Chemical composition, tocopherol and carotenoid content of seeds from

different Andean lupin (*Lupinus mutabilis)* ecotypes. Plant Foods Hum. Nutr. 2021, 76, 98–104.

32. Jacobsen, S.-E.; Mujica, A. Geographical distribution of the Andean lupin (*Lupinus mutabilis Sweet*). Plant Genet. Res. Newslett 2008, 155, 1–8.

33. Naeem, M.; Shabbir, A.; Ansari, A.A.; Aftab, T.; Khan, M.M.A.; Uddin, M. Hyacinth bean *(Lablab purpureus* L.)–An underutilized crop with future potential. Sci. Hortic. 2020, 272, 109551.

34. Bhatt, K.; Malav, P.K.; Gore, P.G.; Tripathi, K.; Rathi, R.; Tiwari, U.L.; Ahlawat, S. A note on distribution and potential of Japanese wild adzuki bean [*Vigna angularis* var. *nipponensis* (Ohwi) Ohwi and H. Ohashi] in India. Genet. Resour. Crop Evol. 2021, 68, 2157–2166.

35. Redden, R.J.; Basford, K.E.; Kroonenberg, P.M.; Islam, F.A.; Ellis, R.; Wang, S.; Cao, Y.; Zong, X.; Wang, X. Variation in adzuki bean (*Vigna angularis*) germplasm grown in China. Crop Sci. 2009, 49, 771–782.

36. Singh, M.; Rundan, V.; Onte, S. Ricebean. Indian Farming 2020, 70, 27–31.

37. Singh, B. Cowpea: The Food Legume of the 21st Century; John Wiley & Sons: Hoboken, NJ, USA, 2020; p. 164.

38. Badiane, F.A.; Diouf, M.; Diouf, D. Cowpea. In Broadening the Genetic Base of Grain Legumes; Springer: Berlin/Heidelberg, Germany, 2014; pp. 95–114.

39. Saxena, A.; Kumar, S.; Raghuvanshi, M.S. Moth bean (*Vigna aconitifolia* (Jacq.) Marechal). In Neglected and Underutilized Crops; Elsevier: Amsterdam, The Netherlands, 2023; pp. 515–537.

40. Gonçalves, L.; Rubiales, D.; Bronze, M.R.; Vaz Patto, M.C. Grass pea (*Lathyrus sativus L.*) - A sustainable and resilient answer to climate challenges. Agronomy 2022, 12, 1324.

41. Upadhyaya, H.D.; Sharma, S.; Reddy, K.; Saxena, R.; Varshney, R.K.; Gowda, C.L. Pigeon pea. In Genetic and Genomic Resources of Grain Legume Improvement; Elsevier: Amsterdam, The Netherlands, 2013; pp. 181–202.

42. Singh, M.; Gautam, N.K.; Rana, M.K.; Dahiya, O.P.; Dutta, M.; Bansal, K.C. Pigeon pea genetic resources and its utilization in India, current status and future prospects. J. Plant Sci. Res 2014, 1, 107.

43. Desire, M.F.; Blessing, M.; Elijah, N.; Ronald, M.; Agather, K.; Tapiwa, Z.; Florence, M.R.; George, N. Exploring food fortification potential of neglected legume and oil seed crops for improving food and nutrition security among smallholder farming communities: A systematic review. J. Agric. Food Res. 2021, 3, 100117.

44. Merga, B.; Haji, J. Economic importance of chickpea: Production, value, and world trade. Cogent Food Agric. 2019, 5, 1615718.

45. Akibode, S.; Maredia, M.K. Global and Regional Trends in Production, Trade and Consumption of Food Legume Crops. 2012. Available online: https://ageconsearch.umn.edu/record/136293/?v=pdf (accessed on 30 October 2024) https://doi.org/10.22004/ag.econ.136293.

46. Nkoana, D.; Gerrano, A.S.; Gwata, E. Agronomic performance and genetic variability of cowpea (*Vigna unguiculata*) Accessions. Legume Res.-Int. J. 2019, 42, 757–762.

47. Adhikari, L.; Hussain, A.; Rasul, G. Tapping the potential of neglected and underutilized food crops for sustainable nutrition security in the mountains of Pakistan and Nepal. Sustainability 2017, 9, 291.

48. Azam-Ali, S.; Ahmadzai, H.; Choudhury, D.; Von Goh, E.; Jahanshiri, E.; Mabhaudhi, T.; Meschinelli, A.; Modi, A.T.; Nhamo, N.; Olutayo, A. Marginal areas and indigenous people: Priorities for research and action. In Science and Innovations for Food Systems Transformation; Springer: Berlin/Heidelberg, Germany, 2021.

49. Majola, N.G.; Gerrano, A.S.; Shimelis, H. Bambara groundnut (*Vigna subterranea* [L.] Verdc.) production, utilisation and genetic improvement in Sub-Saharan Africa. Agronomy 2021, 11, 1345.

50. Bebeli, P.J.; Lazaridi, E.; Chatzigeorgiou, T.; Suso, M.-J.; Hein, W.; Alexopoulos, A.A.; Canha, G.; Van Haren, R.J.; Jóhannsson, M.H.; Mateos, C. State and progress of andean lupin cultivation in Europe: A review. Agronomy 2020, 10, 1038.

51. Cheng, X.; Tian, J. Status and future perspectives of Vigna (mungbean and azuki bean) production and research in China. In The 14th NIAS International Workshop on Genetic Resources–Genetic Resources and Comparative Genomics of Legumes (Glycine and Vigna); National Institute of Agrobiological Science: Tsukuba, Japan, 2011; pp. 83–86.

52. Harouna, D.V.; Venkataramana, P.B.; Ndakidemi, P.A.; Matemu, A.O. Under-exploited wild Vigna species potentials in human and animal nutrition: A review. Glob. Food Secur. 2018, 18, 1–11.

53. Omotayo, A.O.; Aremu, A.O. Marama bean [*Tylosema esculentum* (Burch.) A. Schreib.]: An indigenous plant with potential for food, nutrition, and economic sustainability. Food Funct. 2021, 12, 2389–2403.

54. Curtain, F.; Grafenauer, S. Plant-based meat substitutes in the flexitarian age: An audit of products on supermarket shelves. Nutrients 2019, 11, 2603.

55. Willett, W.; Rockström, J.; Loken, B.; Springmann, M.; Lang, T.; Vermeulen, S.; Garnett, T.; Tilman, D.; DeClerck, F.; Wood, A. Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 2019, 393, 447–492.

56. McMichael, A.J.; Powles, J.W.; Butler, C.D.; Uauy, R. Food, livestock production, energy, climate change, and health. Lancet 2007, 370, 1253–1263.

57. Maphosa, Y.; Jideani, V.A. The role of legumes in human nutrition. Funct. Food-Improv. Health Through Adequate Food 2017, 1, 103–120. https://doi.org/10.5772/intechopen.69127.

58. Fery, R.L. New opportunities in Vigna. In Trends in New Crops and New Use; ASHS Press: Alexandria, VA, USA, 2002; pp. 424–428.

59. Murevanhema, Y.Y.; Jideani, V.A. Potential of bambara groundnut (*Vigna subterranea* (L.) Verdc) milk as a probiotic beverage—A review. Crit. Rev. Food Sci. Nutr. 2013, 53, 954–967.

60. Mayes, S.; Ho, W.K.; Chai, H.H.; Gao, X.; Kundy, A.C.; Mateva, K.I.; Zahrulakmal, M.; Hahiree, M.K.I.M.; Kendabie, P.; Licea, L.C. Bambara groundnut: An exemplar underutilized legume for resilience under climate change. Planta 2019, 250, 803–820.

61. Doxastakis, G. Lupin seed proteins. In Developments in Food Science; Elsevier: Amsterdam, The Netherlands, 2000; Volume 41, pp. 7–38.

62. Rubatzky, V.E.; Yamaguchi, M.; Rubatzky, V.E.; Yamaguchi, M. Peas, Beans, and Other Vegetable Legumes: Family: Fabaceae (Leguminosae). In World Vegetables: Principles, Production, and Nutritive Values; Springer: Berlin/Heidelberg, Germany, 1997; pp. 474–531.

63. Mohan, N.; Mellem, J.J. Functional properties of the protein isolates of hyacinth bean [Lablab purpureus (L.) Sweet]: An effect of the used procedures. LWT 2020, 129, 109572. https://doi.org/10.1016/j.lwt.2020.109572.

64. Katoch, R. Nutritional potential of rice bean (*Vigna umbellata*): An underutilized legume. J. Food Sci. 2013, 78, C8–C16.

65. Mamiro, P.; Mbwaga, A.; Mamiro, D.; Mwanri, A.; Kinabo, J. Nutritional quality and utilization of local and improved cowpea varieties in some regions in Tanzania. Afr. J. Food Agric. Nutr. Dev. 2011, 11, 4490–4506.

66. Lo, S.; Muñoz-Amatriaín, M.; Boukar, O.; Herniter, I.; Cisse, N.; Guo, Y.-N.; Roberts, P.A.; Xu, S.; Fatokun, C.; Close, T.J. Identification of QTL controlling domestication-related traits in cowpea (Vigna unguiculata L. Walp). Sci. Rep. 2018, 8, 6261.

67. Gondwe, T.M.; Alamu, E.O.; Mdziniso, P.; Maziya-Dixon, B. Cowpea (*Vigna unguiculata* (L.) Walp) for food security: An evaluation of end-user traits of improved varieties in Swaziland. Sci. Rep. 2019, 9, 15991.

68. Bhardwaj, H.L.; Hamama, A.A. Oil and fatty acid composition of tepary bean seed. HortScience 2005, 40, 1436–1438.

69. Heredia-Rodríguez, L.; Gaytán-Martínez, M.; Morales-Sánchez, E.; de Jesús Garza-Juárez, A.; Urias-Orona, V.; González-Martínez, B.E.; Lomelí, M.L.-C.; Vázquez-Rodríguez, J.A. Nutritional and technological properties of Tepary bean (*Phaseolus acutifolius*) cultivated in Mexican Northeast. Czech J. Food Sci. 2019, 37, 62–68.

70. Holse, M.; Husted, S.; Hansen, Å. Chemical composition of marama bean (*Tylosema esculentum*) - A wild African bean with unexploited potential. J. Food Compos. Anal. 2010, 23, 648–657.

71. Halimi, R.A.; Barkla, B.J.; Mayes, S.; King, G.J. The potential of the underutilized pulse Bambara groundnut (*Vigna subterranea* (L.) Verdc.) for nutritional food security. J. Food Compos. Anal. 2019, 77, 47–59.

72. Tan, X.L.; Azam-Ali, S.; Goh, E.V.; Mustafa, M.; Chai, H.H.; Ho, W.K.; Mayes, S.; Mabhaudhi, T.; Azam-Ali, S.; Massawe, F. Bambara groundnut: An underutilized leguminous crop for global food security and nutrition. Front. Nutr. 2020, 7, 601496.

73. Carvajal-Larenas, F.; Linnemann, A.; Nout, M.; Koziol, M.; Van Boekel, M. *Lupinus mutabilis*: Composition, uses, toxicology, and debittering. Crit. Rev. Food Sci. Nutr. 2016, 56, 1454–1487.

74. Hossain, S.; Ahmed, R.; Bhowmick, S.; Mamun, A.A.; Hashimoto, M. Proximate composition and fatty acid analysis of *Lablab purpureus* (L.) legume seed: Implicates to both protein and essential fatty acid supplementation. Springerplus 2016, 5, 1899.

75. Yadav, U.; Singh, N.; Kaur, A.; Thakur, S. Physico-chemical, hydration, cooking, textural and pasting properties of different adzuki bean (*Vigna angularis*) accessions. J. Food Sci. Technol. 2018, 55, 802–810.

76. Pattanayak, A.; Roy, S.; Sood, S.; Iangrai, B.; Banerjee, A.; Gupta, S.; Joshi, D.C. Rice bean: A lesser known pulse with well-recognized potential. Planta 2019, 250, 873–890.

77. Carvalho, M.; Lino-Neto, T.; Rosa, E.; Carnide, V. Cowpea: A legume crop for a challenging environment. J. Sci. Food Agric. 2017, 97, 4273–4284.

78. Gondwe, T.M.; Alamu, E.O.; Mdziniso, P.; Maziya-Dixon, B. Cowpea (*Vigna unguiculata* (L.) Walp) for food security: An evaluation of end-user traits of improved varieties in Swaziland. Sci. Rep. 2019, 9, 15991.

79. Deshmukh, B; Pawar, V. Effects of different pretreatments on physicochemical and anti-nutritional quality of moth bean. J. Pharmacogn. Phytochem. 2020, 9, 1965–1968.

80. Hailu, D.; Abera, S.; Teka, T.A.; Box, P.; Jimma, E. Effects of Processing on Nutritional Composition and Anti-Nutritional Factors of Grass pea (*Lathyrus sativus L.*): A review. Food Sci. Qual. Manag. 2015, 36, 61–71.

81. Lambein, F.; Travella, S.; Kuo, Y.-H.; Van Montagu, M.; Heijde, M. Grass pea (*Lathyrus sativus L.*): Orphan crop, nutraceutical or just plain food? Planta 2019, 250, 821–838.

82. Amarteifio, J.; Munthali, D.; Karikari, S.; Morake, T. The composition of pigeon peas (*Cajanus cajan* (L. Millsp.) grown in Botswana. Plant Foods Hum. Nutr. 2002, 57, 173–177.

83. Tharanathan, R.; Mahadevamma, S. Grain legumes - A boon to human nutrition. Trends Food Sci. Technol. 2003, 14, 507–518.

84. Celmeli, T.; Sari, H.; Canci, H.; Sari, D.; Adak, A.; Eker, T.; Toker, C. The nutritional content of common bean (*Phaseolus vulgaris* L.) landraces in comparison to modern varieties. Agronomy 2018, 8, 166.

85. Carmona-García, R.; Osorio-Díaz, P.; Agama-Acevedo, E.; Tovar, J.; Bello-Pérez, L.A. Composition and effect of soaking on starch digestibility of *Phaseolus vulgaris* (L.) cv.'Mayocoba'. Int. J. Food Sci. Technol. 2007, 42, 296–302.

86. Asibuo, J.Y.; Akromah, R.; Safo-Kantanka, O.; Adu-Dapaah, H.K.; Ohemeng-Dapaah, S.; Agyeman, A. Chemical composition of groundnut, *Arachis hypogaea* (L.) landraces. Afr. J. Biotechnol. 2008, 7, 2203–2208.

87. Singhai, B.; Shrivastava, S. Nutritive value of new chickpea (*Cicer arietinum L.*) varieties. J. Food Agric. Environ. 2006, 4, 48.

88. Chen, S.-K.; Lin, H.-F.; Wang, X.; Yuan, Y.; Yin, J.-Y.; Song, X.-X. Comprehensive analysis in the nutritional composition, phenolic species and in vitro antioxidant activities of different pea cultivars. Food Chem. X 2023, 17, 100599.

89. Kachave, K.; Pawar, V.; Shinde, E. Effect of germination treatment on chemical and nutritional properties of horse gram. Pharma Innov. J. 2020, 9, 213-216.

90. Katoch, R.; Sanadya, S.K.; Pathania, K.; Chaudhary, H. Nutritional and nutraceutical potential of rice bean (*Vigna umbellata*) - A legume with hidden potential. Front. Nutr. 2023, 10, 1126544.

91. Oyeleke, G.; Afolabi, O.; Isola, A. Some quality characteristics and carbohydrate fractions of Bambara groundnut (*Vigna subterranea L.*) seed flour. J. Appl. Chem 2012, 2, 16–19.

92. Khetarpaul, N. Total mineral content present (calcium, magnesium, potassium, phosphorus, iron, zinc, manganese, copper, and boron and nickel) in leaves of Desi and Kabuli chickpea varieties (on dry matter basis). Int. J. Commun. Syst. 2018, 6, 633–635.

93. Sheerens, J.; Tinsley, A.; Abbas, I.; Weber, C.; Berry, J. The nutritional significance of tepary bean consumption. Desert Plants 1983, 5, 11–56.

94. Abdou Bouba, A.; Njintang Yanou, N.; Foyet, H.; Scher, J.; Montet, D.; Mbofung, C.M. Proximate composition, mineral and vitamin content of some wild plants used as spices in Cameroon. Food Nutr. Sci. 2012, 3, 423–432. https://doi.org/10.4236/fns.2012.34061.

95. Abdulsalami, M.; Sheriff, H. Effect of processing on the proximate composition and mineral content of Bambara groundnut (*Voandezeia subterranean*). Bayero J. Pure Appl. Sci. 2010, 3, 188–190. https://doi.org/10.4314/bajopas.v3i1.58781.

96. Musah, M.; Azeh, Y.; Mathew, J.T.; Nwakife, N.C.; Mohammed, A.I.; Saidu, F. Nutritional evaluation of Bambara groundnut (*Vigna subterranea* (L.) Verdc) from Lapai, Nigeria. Afr. J. Agric. Food Sci. 2021, 4, 32–39. https://doi.org/10.52589/AJAFS_SQI5U7CN.

97. Tizazu, H.; Emire, S.A. Chemical composition, physicochemical and functional properties of lupin (*Lupinus albus*) seeds grown in Ethiopia. Afr. J. Food Agric. Nutr. Dev. 2010, 10, 3029–3046. https://doi.org/10.4314/ajfand.v10i8.60895.

98. Ademola, O.A.; Abioye, O. Proximate composition, mineral content and mineral safety index of Lablab purpureus seed flour. Int. J. Sci. Healthc. Res. 2017, 2, 44–50.

99. Sombie, P.A.; Ouedraogo, I.; Tignegré, J.B.D.; Hilou, A.; Ouedraogo, T.J.; Kiendrébéogo, M. Genotypic variation of mineral elements and phytate levels of thirty cowpeas (*Vigna unguiculata L. Walp*.) varieties cultivated in Burkina Faso. J. Food Chem. Nutr. 2018, 6, 13–20.

100. Ampah, J.K. Assessment of Nutritional Level, Functional Properties and Mineral Contents of Newly Developed Genotypes of Cowpea [*Vigna unguiculata (L.) Walp*.] in Ghana. Master's Thesis, University of Cape Coast, Cape Coast, Ghana, 2020.

101. Hajjagana, L.H.; Sheriff, M.; Alhaji, M.A. Evaluation of the chemical composition, anti-nutrients and mineral element level of a composite meal from pearl millet, wheat, cowpea and groundnut. Sky J. Food Sci. 2014, 3, 61–70.

102. Pandarinathan, S. Biochemical status of moth bean in various genotypes. Pharma Innov. J. 2023, 12, 749–754.

103. Urga, K.; Fufa, H.; Biratu, E.; Husain, A. Peer reviewed article no 10-evaluation of lathyrus sativus cultivated in Ethiopia for proximate composition, minerals, â-odap and anti-nutritional components. Afr. J. Food Agric. Nutr. Dev. 2005, 5, 1–16.

104. Aderonke, A.M.; Fashakin, J.B.; Ibironke, S.I. Determination of mineral contents, proximate composition and functional properties of complementary diets prepared from maize, soybean and pigeon pea. Am. J. Nutr. Food Sci. 2014, 1, 53–56.

105. Etiosa, O.; Chika, N.; Benedicta, A. Mineral and proximate composition of soya bean. Asian J. Phys. Chem. Sci. 2018, 4, 1–6.

106. Fetahu, S.; Aliu, S.; Rusinovci, I.; Behluli, A.; Kelmendi, B. Genetic diversity for micronutrients contents in some common bean landraces (*Phaseolus vulgaris L.*). In

Proceedings of the 49th Croatian and 9th International Symposium on Agriculture, Dubrovnik, Croatia, 16–21 February 2014; pp. 16–21.

107. Ada, R.; Ceyhan, E.; Çelik, Ş.A.; Harmankaya, M.; Özcan, M.M. Fatty acid composition and mineral contents of pea genotype seeds. Iran. J. Chem. Chem. Eng. (IJCCE) 2019, 38, 153–158.

108. Micha, R.; Mannar, V.; Afshin, A.; Allemandi, L.; Baker, P.; Battersby, J.; Bhutta, Z.; Chen, K.; Corvalan, C.; Di Cesare, M. 2020 Global Nutrition Report: Action on Equity to End Malnutrition; Development Initiatives: Bristol, UK, 2020; p. 172.

109. Fanzo, J.; Hawkes, C.; Udomkesmalee, E.; Afshin, A.; Allemandi, L.; Assery, O.; Baker, P.; Battersby, J.; Bhutta, Z.; Chen, K. 2018 Global Nutrition Report; Global Nutrition Report: London, UK, 2019.

110. Rukuni, M. Africa: Addressing growing threats to food security. J. Nutr. 2002, 132, 3443S–3448S.

111. Haq, N. Underutilized food legumes: Potential for multipurpose uses. In Biology and Breeding of Food Legumes; CABI: Wallingford UK, 2011; pp. 329–347.

112. Heuzé, V.; Tran, G.; Sauvant, D.; Bastianelli, D.; Lebas, F. Lima bean (*Phaseolus lunatus*). 2015. Available online: https://agritrop.cirad.fr/582485/7/ID582485_ENG.pdf (accessed on 30 October 2024).

113. Alves, A.U.; de Oliveira, A.P.; Alves, A.U.; Dornelas, C.S.; Alves, E.U.; Cardoso, E.A.; de Oliveira, A.N.P.; Cruz, I.d.S. Lima beans production and economic revenue as function of organic and mineral fertilization. Hortic. Bras. 2008, 26, 251–254.

114. Apata, D.; Ologhobo, A. Biochemical evaluation of some Nigerian legume seeds. Food Chem. 1994, 49, 333–338.

115. Tope, A.K. Microbiological analyses and nutrient composition of sorghum co-fermented with Lima bean seeds. Curr. Res. Microbiol. Biotechnol. 2014, 2, 431–437.

116. Sobowale, S.S.; Animashaun, O.H.; Omosebi, O.M. Influence of traditional and back-slopping steeping methods on some quality attributes of lima bean-sorghum composite flour and its bread making potential. J. Food Process. Preserv. 2021, 45, e15030.

117. Adebayo, S. Effect of soaking time on the proximate, mineral compositions and anti-nutritional factors of lima bean. Food Sci. Qual. Manag. 2014, 27, 2224–6088.

118. El-Gohery, S.S. Effect of different treatments on nutritional value of lima bean (Phaseolus lunatus) and its utilization in biscuit manufacture. Food Nutr. Sci. 2021, 12, 372–391.

119. Lambein, F.; Kuo, Y.-H.; Ikegami, F.; Kusama-Eguchi, K.; Enneking, D. Grain legumes and human health. In Proceedings of the Fourth International Food Legumes Research Conference (IFLRC-IV), New Delhi, India, 18–22 October 2005; pp. 422–432.

120. Ross, A.C.; Caballero, B.; Cousins, R.J.; Tucker, K.L. Modern Nutrition in Health and Disease; Jones & Bartlett Learning: Burlington, MA, USA, 2020.

121. Naiker, T.S. Effects of Processing on the Characteristics of Flour and Protein Isolates Produced from Lablab Purpureus. Doctoral Dissertation, Durban University of Technology, Durban, South Africa, 2020. https://doi.org/10.51415/10321/3601.

122. Bazzano, L.A. Effects of soluble dietary fiber on low-density lipoprotein cholesterol and coronary heart disease risk. Curr. Atheroscler. Rep. 2008, 10, 473–477.

123. Zhang, H.; Du, M.; Yang, Q.; Zhu, M.-J. Butyrate suppresses murine mast cell proliferation and cytokine production through inhibiting histone deacetylase. J. Nutr. Biochem. 2016, 27, 299–306.

124. Aune, D.; De Stefani, E.; Ronco, A.; Boffetta, P.; Deneo-Pellegrini, H.; Acosta, G.; Mendilaharsu, M. Legume intake and the risk of cancer: A multisite case–control study in Uruguay. Cancer Causes Control 2009, 20, 1605–1615.

125. Wang, Y.; Wang, Z.; Fu, L.; Chen, Y.; Fang, J. Legume consumption and colorectal adenoma risk: A meta-analysis of observational studies. PLoS ONE 2013, 8, e67335.

126. Kondo, A.; Morota, N.; Date, H.; Yoshifuji, K.; Morishima, T.; Miyazato, M.; Shirane, R.; Sakai, H.; Pooh, K.H.; Watanabe, T. Awareness of folic acid use increases its consumption, and reduces the risk of spina bifida. Br. J. Nutr. 2015, 114, 84–90.

127. Kouris-Blazos, A.; Belski, R. Health benefits of legumes and pulses with a focus on Australian sweet lupins. Asia Pac. J. Clin. Nutr. 2016, 25, 1–17.

128. Mall, T. Diversity of underexploited pulses in Bahraich (*Uttar Pradesh*) India. Eur. J. Biomed. Pharmaceut. Sci 2017, 4, 196–215.

129. Bhadkaria, A.; Narvekar, D.T.; Gupta, N.; Khare, A.; Bhagyawant, S.S. Moth bean (*Vigna aconitifolia* (Jacq.) Marechal) seeds: A review on nutritional properties and health benefits. Discov. Food 2022, 2, 18.

130. Rani, J.; Dhull, S.B.; Kinabo, J.; Kidwai, M.K.; Sangwan, A. A narrative review on nutritional and health benefits of underutilized summer crop to address agriculture challenges: Moth bean (*Vigna aconitifolia* L.). Legum. Sci. 2023, 5, e204.

131. Smith, A.P. Legumes and well-being in the elderly: A preliminary study. J. Food Res. 2012, 1, 165.

132. Lee, S.H.; Jin, N.; Paik, D.-J.; Kim, D.-Y.; Chung, I.-M.; Park, Y. Consumption of legumes improves certain bone markers in ovariectomized rats. Nutr. Res. 2011, 31, 397–403.

133. Pischon, T.; Girman, C.J.; Hotamisligil, G.S.; Rifai, N.; Hu, F.B.; Rimm, E.B. Plasma adiponectin levels and risk of myocardial infarction in men. JAMA 2004, 291, 1730–1737.

134. Cena, H.; Chieppa, M. Coronavirus disease (COVID-19–SARS-CoV-2) and nutrition: Is infection in Italy suggesting a connection? Front. Immunol. 2020, 11, 944.

135.Thi, H.H.P.; Nguyen, T.L. Nutraceutical properties of legume seeds: Phytochemical compounds. In Legumes Research-Volume 2; IntechOpen: London, UK, 2021.

136. Espíndola, K.M.M.; Ferreira, R.G.; Narvaez, L.E.M.; Silva Rosario, A.C.R.; Da Silva, A.H.M.; Silva, A.G.B.; Vieira, A.P.O.; Monteiro, M.C. Chemical and pharmacological aspects of caffeic acid and its activity in hepatocarcinoma. Front. Oncol. 2019, 9, 541.

137. Nyau, V.; Prakash, S.; Rodrigues, J.; Farrant, J. Profiling of phenolic compounds in sprouted common beans and Bambara groundnuts. J. Food Res. 2017, 6, 74–82.

138. Kahkeshani, N.; Farzaei, F.; Fotouhi, M.; Alavi, S.S.; Bahramsoltani, R.; Naseri, R.; Momtaz, S.; Abbasabadi, Z.; Rahimi, R.; Farzaei, M.H. Pharmacological effects of gallic acid in health and diseases: A mechanistic review. Iran. J. Basic Med. Sci. 2019, 22, 225.

139. Dube, P.S.; Braganza, V.J.; Jain, N.K. Phytochemical estimation of moth bean seed extracts. Int. J. Res. Anal. Rev. 2022, 9, 544–551.

140. Al-Saeedi, A.H.; Hossain, M.A. Total phenols, total flavonoids contents and free radical scavenging activity of seeds crude extracts of pigeon pea traditionally used in Oman for the treatment of several chronic diseases. Asian Pac. J. Trop. Dis. 2015, 5, 316–321.

141. Avanza, M.V.; Álvarez-Rivera, G.; Cifuentes, A.; Mendiola, J.A.; Ibáñez, E. Phytochemical and functional characterization of phenolic compounds from cowpea (Vigna unguiculata (L.) Walp.) obtained by green extraction technologies. Agronomy 2021, 11, 162.

142. Sharma, N.; Tiwari, N.; Vyas, M.; Khurana, N.; Muthuraman, A.; Utreja, P. An overview of therapeutic effects of vanillic acid. Plant Arch. 2020, 20, 3053–3059.

143. Sangsukiam, T.; Duangmal, K. Changes in bioactive compounds and health-promoting activities in adzuki bean: Effect of cooking conditions and in vitro simulated gastrointestinal digestion. Food Res. Int. 2022, 157, 111371.

144. Kakkar, S.; Bais, S. A review on protocatechuic acid and its pharmacological potential. ISRN Pharmacol. 2014, 2014, 952943. https://doi.org/10.1155/2014/952943.

145. Srinivasulu, C.; Ramgopal, M.; Ramanjaneyulu, G.; Anuradha, C.; Kumar, C.S. Syringic acid (SA) - a review of its occurrence, biosynthesis, pharmacological and industrial importance. Biomed. Pharmacother. 2018, 108, 547–557.

146. Manuja, R.; Sachdeva, S.; Jain, A.; Chaudhary, J. A comprehensive review on biological activities of p-hydroxy benzoic acid and its derivatives. Int. J. Pharm. Sci. Rev. Res 2013, 22, 109–115.

147. Sodedji, F.A.K.; Ryu, D.; Choi, J.; Agbahoungba, S.; Assogbadjo, A.E.; N'Guetta, S.-P.A.; Jung, J.H.; Nho, C.W.; Kim, H.-Y. Genetic diversity and association analysis for carotenoid content among sprouts of cowpea (*Vigna unguiculata L. Walp*). Int. J. Mol. Sci. 2022, 23, 3696.

148. Srinivasan, M.; Sudheer, A.R.; Menon, V.P. Ferulic acid: Therapeutic potential through its antioxidant property. J. Clin. Biochem. Nutr. 2007, 40, 92–100.

149. Ganeshpurkar, A.; Saluja, A.K. The pharmacological potential of rutin. Saudi Pharm. J. 2017, 25, 149–164.

150. Okafor, J.N.; Meyer, M.; Le Roes-Hill, M.; Jideani, V.A. Flavonoid and phenolic acid profiles of dehulled and whole Vigna subterranea (L.) Verdc seeds commonly consumed in South Africa. Molecules 2022, 27, 5265.

151. Isemura, M. Catechin in human health and disease. Molecules 2019, 24, 528.

152. Dinore, J.M.; Farooqui, M. GC-MS and LC-MS: An integrated approach towards the phytochemical evaluation of methanolic extract of Pigeon Pea [*Cajanus cajan* (L.) Millsp] leaves. Nat. Prod. Res. 2022, 36, 2177–2181.

153. Arise, A.K.; Amonsou, E.O.; Ijabadeniyi, O.A. Influence of extraction methods on functional properties of protein concentrates prepared from South African Bambara groundnut landraces. Int. J. Food Sci. Technol. 2015, 50, 1095–1101.

154 Harris, T.; Jideani, V.; Le Roes-Hill, M. Flavonoids and tannin composition of Bambara groundnut (Vigna subterranea) of Mpumalanga, South Africa. Heliyon 2018, 4, e00833.

155. Kritchevsky, D.; Chen, S.C. Phytosterols-Health benefits and potential concerns: A review. Nutr. Res. 2005, 25, 413–428.

156. Mudryj, A.N.; Yu, N.; Aukema, H.M. Nutritional and health benefits of pulses. Appl. Physiol. Nutr. Metab. 2014, 39, 1197–1204.

157. Ajibola, C.F.; Malomo, S.A.; Fagbemi, T.N.; Aluko, R.E. Polypeptide composition and functional properties of African yam bean seed (*Sphenostylis stenocarpa*) albumin, globulin and protein concentrate. Food Hydrocoll. 2016, 56, 189–200.

158. Kumar, J.; Roy, J.D.; Minhas, A.S. Knowledge level of Ayurveda practitioner on public health. AYU 2014, 35, 9.

159. Li, H.; Zou, L.; Li, X.Y.; Wu, D.T.; Liu, H.Y.; Li, H.B.; Gan, R.Y. Adzuki bean (*Vigna angularis*): Chemical compositions, physicochemical properties, health benefits, and food applications. Compr. Rev. Food Sci. Food Saf. 2022, 21, 2335–2362.

160. Barman, A.; Marak, C.M.; Barman, R.M.; Sangma, C.S. Nutraceutical properties of legume seeds and their impact on human health. In Legume Seed Nutraceutical Research; IntechOpen: London, UK, 2018.

161. Campos-Vega, R.; Loarca-Piña, G.; Oomah, B.D. Minor components of pulses and their potential impact on human health. Food Res. Int. 2010, 43, 461–482.

162. Kumar Tiwari, A.; Abhinay, B.; Suresh Babu, K.; Kumar, D.A.; Zehra, A.; Madhusudana, K. Pigeon pea seed husks as potent natural resource of anti-oxidant and anti-hyperglycaemic activity. Int. J. Green Pharm. 2013, 7, 252.

163. Scarafoni, A.; Kumar, J.; Magni, C.; Sironi, E.; Duranti, M. Biologically active molecules and nutraceutical properties of legume seeds. IFLRC IV 2005, 18–22

164. Rüdiger, H.; Gabius, H.-J. Plant lectins: Occurrence, biochemistry, functions and applications. Glycoconj. J. 2001, 18, 589–613.

165. Racette, S.B.; Spearie, C.A.; Phillips, K.M.; Lin, X.; Ma, L.; Ostlund, R.E., Jr. Phytosterol-deficient and high-phytosterol diets developed for controlled feeding studies. J. Am. Diet. Assoc. 2009, 109, 2043–2051.

166. Thompson, L.U. Potential health benefits and problems associated with antinutrients in foods. Food Res. Int. 1993, 26, 131–149.

167. Banerji, A.; Fernandes, A.; Bane, S.; Ahire, S. The field bean protease inhibitor has the potential to suppress B16F10 melanoma cell lung metastasis in mice. Cancer Lett. 1998, 129, 15–20.

168. Clemente, A.; MacKenzie, D.; Johnson, I.; Domoney, C. Investigation of legume seed protease inhibitors as potential anti-carcinogenic proteins. Publ.-Eur. Assoc. Anim. Prod. 2004, 110, 137–142.

169. Klomklao, S.; Benjakul, S.; Kishimura, H.; Osako, K.; Tanaka, M. A heat-stable trypsin inhibitor in adzuki bean (Vigna angularis): Effect of extraction media, purification and biochemical characteristics. Int. J. Food Sci. Technol. 2010, 45, 163–169.

170. Forman, R.T.; Wu, J.J. Where are the best places for the next billion people? Think globally, plan regionally. In Handbook on Biodiversity and Ecosystem Services in Impact Assessment; Edward Elgar Publishing: Cheltenham, UK, 2016; pp. 453–474.

171. Hanjra, M.A.; Qureshi, M.E. Global water crisis and future food security in an era of climate change. Food Policy 2010, 35, 365–377.

172. Temba, M.C.; Njobeh, P.B.; Adebo, O.A.; Olugbile, A.O.; Kayitesi, E. The role of compositing cereals with legumes to alleviate protein energy malnutrition in Africa. Int. J. Food Sci. Technol. 2016, 51, 543–554.

173. Di Stefano, E.; Agyei, D.; Njoku, E.N.; Udenigwe, C.C. Plant RuBisCo: An underutilized protein for food applications. J. Am. Oil Chem. Soc. 2018, 95, 1063–1074.

174. Pokhrel, S. Legumes crop rotation can improve food and nutrition security in Nepal. Agron. J. Nepal 2013, 3, 123–127.

175. Matusso, J.; Mugwe, J.; Mucheru-Muna, M. Potential role of cereal-legume intercropping systems in integrated soil fertility management in smallholder farming systems of Sub-Saharan Africa. Res. J. Agric. Environ. Manag. 2014, 3, 162–174.

176. Mahmood, F.; Shahzad, T.; Hussain, S.; Shahid, M.; Azeem, M.; Wery, J. Grain legumes for the sustainability of European farming systems. In Sustainable Agriculture Reviews 32: Waste Recycling and Fertilisation; Springer: Berlin/Heidelberg, Germany, 2018; pp. 5–133.

177. Gowda, C.L.; Samineni, S.; Gaur, P.; Saxena, K. Enhancing the productivity and production of pulses in India. In Climate Change and Sustainable Food Security; National Institute of Advanced Studies: Bangalore, Indian, 2013; pp. 145–159.

178. Watson, C.A.; Reckling, M.; Preissel, S.; Bachinger, J.; Bergkvist, G.; Kuhlman, T.; Lindström, K.; Nemecek, T.; Topp, C.F.; Vanhatalo, A. Grain legume production and use in European agricultural systems. Adv. Agron. 2017, 144, 235–303.

179. Muluneh, M.G. Impact of climate change on biodiversity and food security: A global perspective - A review article. Agric. Food Secur. 2021, 10, 1–25.

180. Khan, M.A.; Tahir, A.; Khurshid, N.; Husnain, M.I.u.; Ahmed, M.; Boughanmi, H. Economic effects of climate change-induced loss of agricultural production by 2050: A case study of Pakistan. Sustainability 2020, 12, 1216.

181. Kahane, R.; Hodgkin, T.; Jaenicke, H.; Hoogendoorn, C.; Hermann, M.; Keatinge, J.; d'Arros Hughes, J.; Padulosi, S.; Looney, N. Agrobiodiversity for food security, health and income. Agron. Sustain. Dev. 2013, 33, 671–693.

182. Makate, C.; Wang, R.; Makate, M.; Mango, N. Crop diversification and livelihoods of smallholder farmers in Zimbabwe: Adaptive management for environmental change. SpringerPlus 2016, 5, 1135.

183. Ali, A.; Bhattacharjee, B. Nutrition security, constraints, and agro-diversification strategies of neglected and underutilized crops to fight global hidden hunger. Front. Nutr. 2023, 10, 1144439.

184. Ogola, J.B.O.; Thangwana, N. Water use efficiency of summer sown chickpea in a tropical environment: Response to genotype and planting density. J. Food Agric. Environ. 2013, 11, 2689–2695.

185. Popoola, J.O.; Aworunse, O.S.; Ojuederie, O.B.; Adewale, B.D.; Ajani, O.C.; Oyatomi, O.A.; Eruemulor, D.I.; Adegboyega, T.T.; Obembe, O.O. The exploitation of orphan legumes for food, income, and nutrition security in Sub-Saharan Africa. Front. Plant Sci. 2022, 13, 782140.

186. Mapfumo, P.; Adjei-Nsiah, S.; Mtambanengwe, F.; Chikowo, R.; Giller, K.E. Participatory action research (PAR) as an entry point for supporting climate change adaptation by smallholder farmers in Africa. Environ. Dev. 2013, 5, 6–22.

187. Prabhu, K.R.; Kumar, A.; Yumkhaibam, R.S.; Janeja, H.S.; Krishna, B.; Talekar, N. A review on conventional and modern breeding approaches for developing climate resilient crop varieties: NA. J. Appl. Nat. Sci. 2023, 15, 987–997.

188. Kumar, S.; Gupta, P.; Barpete, S.; Choukri, H.; Maalouf, F.; Sarkar, A. Grass pea. In The Beans and the Peas; Woodhead Publishing: Cambridge, UK, 2021; pp.273–287.

189. Rubiales, D.; Emeran, A.A.; Flores, F. Adaptation of grass pea (Lathyrus sativus) to Mediterranean environments. Agronomy 2020, 10, 1295.

190. Fatokimi, E.O.; Tanimonure, V.A. Analysis of the current situation and future outlooks for pigeon pea (Cajanus Cajan) production in Oyo State, Nigeria: A Markov Chain model approach. J. Agric. Food Res. 2021, 6, 100218.

191. Bower, N.; Hertel, K.; Oh, J.; Storey, R. Nutritional evaluation of marama bean (*Tylosema esculentum*, Fabaceae): Analysis of the seed. Econ. Bot. 1988, 42, 533–540.

192. Sharma, P., Goudar, G., Chandragiri, A.K., Ananthan, R., Subhash, K., Chauhan, A., Longvah, T., Singh, M., Bhardwaj, R., Parida, S.K. and Singh, A.K., 2023. Assessment of diversity in anti-nutrient profile, resistant starch, minerals and carbohydrate components in different ricebean (Vigna umbellata) accessions. Food Chemistry, 405, p.134835.

Chapter 3: Socioeconomic Factors Influencing Crop Diversification Among Smallholder Farmers in Bergville, South Africa

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Abstract

Crop diversification is a vital strategy for achieving sustainable agriculture and food security; however, its adoption rates remain low. This study examined the socioeconomic factors influencing crop diversification among smallholder farmers. A two-stage sampling procedure was employed to collect data from 161 farmers who specialised solely in crop production. A structured questionnaire was used to collect data, analysed using descriptive statistics. The multiple linear regression and multivariate probit regression models were applied to assess the socioeconomic factors influencing diversification. The results revealed that smallholders primarily focused on vegetable cultivation (87%), followed by cereals (56%) and legumes (43%). Education level, household size, market access, and the perceived benefits of diversification significantly influenced diversification decisions ($p < 0.05$). Also, sources of irrigation water, age, marital status, and farm size were key factors in vegetable diversification, while farming experience, farm size, and perceived benefits influenced legume diversification. Only marital status and farming experience were positively linked to cereal crop diversification. Furthermore, 48.4% of farmers practice intercropping, integrating maize with pumpkins or sugar beans, while 33.5% still rely on monoculture, predominantly maize, due to limited resources. These findings underscore the need for policies and extension support to address socioeconomic barriers and promote the wider adoption of crop diversification strategies.

Keywords: farming practices; cropping patterns; smallholder farmers; multivariate probit regression model; socioeconomic attributes

3.1 Introduction

Smallholder farming is a vital component of South Africa's agricultural sector, playing a crucial role in ensuring food security, enhancing rural livelihoods, and promoting economic development [1,2]. However, smallholder farmers face numerous challenges, including climate variability, soil degradation, limited market access, financial constraints, and inadequate infrastructure [3,4]. Despite the increasing threats posed by climate change, many smallholder farmers continue cultivating the same staple crops, often relying on monoculture systems [5]. These factors increase the vulnerability of smallholder farming systems, thereby reducing agricultural productivity and resilience while exacerbating food insecurity and poverty in rural communities [6]. To enhance resilience and productivity, adaptive strategies such as crop diversification have become increasingly essential [7]. Crop di-versification has been recognized as an ecologically sustainable and cost-effective strategy for agricultural intensification. This approach involves integrating multiple crop species within a farming system through practices such as crop rotation, multiple cropping, or intercropping [8].

According to Barman et al. [8] and Zou et al. [9], this strategy enhances soil fertility, reduces pest and disease prevalence, and minimizes agrochemical inputs by de-creasing reliance on nitrogen-based fertilizers, particularly when leguminous crops are incorporated into cropping systems [10]. Furthermore, crop diversification enables farmers to adapt to shifting consumer preferences and market dynamics, potentially increasing profitability, stabilizing income, and enhancing resilience to climatic and economic shocks [11–13]. As noted by Shikwambana et al. [14], crop diversification enhances climate resilience in South Africa by reducing the vulnerability of small-holder farmers to climatic shocks such as droughts, irregular rainfall, and temperature extremes. Through the cultivation of diverse crops with various tolerances to water stress, pests, and diseases, farmers can mitigate the risk of total crop failure associated with climate variability. In the South African context, characterized by semi-arid conditions, high interannual rainfall variability, and frequent droughts, diversification al-lows for more stable income streams and food security.

Moreover, crop diversification benefits the poorest the most and raises farmers out of poverty [15]. While diversification is generally associated with reductions in poverty levels, existing poverty may constrain farmers' ability to effectively manage multiple crops. Due to limited agricultural resources, resource-poor farmers are likely to prioritize the cultivation of staple crops with high caloric yields to meet basic subsistence needs, potentially limiting their capacity to diversify [16]. From a food security perspective, crop diversification is crucial for sustaining both the quantity and nutritional quality of food production. It contributes to a more stable and balanced food supply, which is particularly vital for vulnerable populations. The inclusion of protein-rich legumes and micronutrient-dense vegetables in smallholder farming systems significantly improves dietary diversity and nutritional outcomes, especially in rural areas where access to affordable, nutrient-rich food is often limited. Despite these well-documented benefits, the adoption of crop diversification remains low among smallholder farmers [17,18].

Smallholder farmers have historically employed diverse cropping systems, utilizing indigenous knowledge to cultivate a variety of crops for household consumption, soil health, and risk mitigation. These practices were tailored to local agroecological conditions and aimed at enhancing resilience. A systematic review highlights that crop diversification, including the use of indigenous and drought-tolerant crop varieties, has been a key strategy for smallholder farmers in South Africa to adapt to climate change impacts on their livelihoods [19]. However, the green revolution introduced high-yielding varieties and modern agricultural techniques, leading many smallholders to adopt monoculture practices [20]. This shift was driven by government incentives and market demands, resulting in reduced crop diversity and increased reliance on a narrow range of staple or cash crops. Research indicates that the promotion of high-yield varieties often led to the displacement of traditional crops, impacting biodiversity and resilience [21]. In response to climate change, market volatility, and declining soil fertility, there has been a renewed interest in crop diversification among smallholder farmers. Integrating drought-resistant and climate-resilient species, as well as reintroducing traditional crops, has been observed as a strategy to enhance in-come, food security, and resilience. A study in Zimbabwe demonstrates that crop di-versification significantly improves crop productivity, household income, food security, and nutrition, underscoring its role as a viable cli-mate-smart agriculture practice [22].

Socio-economic factors, including limited access to land, water, credit, and agricultural technologies, along with policy and institutional barriers, such as insufficient government support and weak market linkages, further constrain the success of crop diversification efforts [23,24]. Inadequate extension services and a lack of technical knowledge hinder the effective implementation of diversification strategies [25,26]. While existing studies have examined the role of crop diversification in mitigating climate risks and enhancing agricultural productivity, most research has primarily focused on large-scale commercial farms. Consequently, there is a lack of empirical data on the determinants and effectiveness of crop diversification practices among smallholder farmers in South Africa. A comprehensive investigation is required to assess the socioeconomic factors influencing crop diversification practices and identify strategies to enhance their adoption, particularly within South Africa's diverse agroecological zones.

This empirical study employed a survey-based research methodology to assess the socioeconomic factors influencing crop diversification among smallholder farmers in South Africa. To achieve this objective, the study examined predominant crops and cropping systems, assessed farmers' knowledge of diversification benefits and training attendance, understanding, and knowledge utilization, and analysed the socioeconomic factors influencing their crop diversification decisions. The study's findings are expected to provide valuable empirical insights to bridge existing knowledge gaps, support policymakers in developing targeted interventions, and strengthen agricultural extension services. The findings will also contribute to a deeper understanding of how socioeconomic factors influence crop diversification among resource-constrained farmers in rural communities of the Global South. Furthermore, this study aligns with the Sustainable Development Goals (SDG 1 and 2), which aim to eradicate hunger, poverty, and malnutrition by 2030, as well as SDG 12 and 13, which promote responsible production and address climate action. The study will provide a roadmap for addressing key gaps that need to be addressed to promote sustainable and climate-resilient farming practices that enhance food security, income stability, and rural livelihoods in smallholder farming systems.

3.1.1 Theoretical Framework for the Study

This study is underpinned by two complementary theoretical approaches: the Theory of Planned Behaviour (TPB) and the Sustainable Livelihood Framework (SLF). These frameworks provide a comprehensive analytical approach to examining the socioeconomic factors of crop diversification decisions among smallholder farmers in Bergville, South Africa. The theory of planned behaviours posits that an individual's intention to perform a specific behaviour, such as adopting crop diversification, is shaped by three core components: attitudes, subjective norms, and perceived behavioural control. In the context of smallholder farming, attitudes reflect farmers' beliefs about the benefits of diversification, such as enhanced food security or income stability. Subjective norms involve social pressures or community expectations, including the influence of farmer cooperatives or local institutions, such as the Farmers Support Group. Perceived behavioural control is especially relevant in Bergville, where access to land, water, markets, and extension services affects farmers' ability to diversify. These three factors collectively shape behavioural intentions, which are strong predictors of actual diversification practices.

Complementing the TPB, the Sustainable Livelihood Framework offers a holistic perspective on the resources and vulnerabilities that influence smallholder farmers' livelihood strategies. The SLF identifies five key asset categories, namely human, social, natural, physical, and financial capital, which interact with external factors such as policies, institutions, and climate variability. In Bergville, access to education (human capital), land and water (natural capital), farming tools (physical capital), and income or credit (financial capital) all influence a farmer's capacity to adopt crop diversification. The framework also emphasizes vulnerability contexts, such as climate shocks, market fluctuations, or pol-icy gaps that may constrain or motivate diversification choices. By integrating TPB and SLF, this study acknowledges that crop diversification is not only a rational decision influenced by individual beliefs and intentions but also a livelihood strategy shaped by broader structural and resource-based constraints. This dual-theoretical approach al-lows for a deeper analysis of how socioeconomic factors collectively determine the ex-tent and nature of crop diversification among smallholder farmers in Bergville.

Based on a synthesis of the reviewed literature, a conceptual framework (Figure 3.1) was developed to illustrate the interactions between the variables measured in the study and how these interrelationships influence crop diversification among small-holder crop farmers. The framework illustrates how the socioeconomic characteristics of smallholder farmers, including age, education level, marital status, household size, farming experience, and farm size, can directly influence their crop diversification decisions. Farmers' perceptions of the benefits of crop diversification, along with their access to key resources such as water, markets, land, and seeds, interact with their socio-economic profiles and are expected to influence their diversification choices. Ultimately, increased crop diversification in smallholder farmers' agricultural practices is anticipated to contribute to enhanced food security, income stability, improved livelihoods, poverty reduction, increased climate resilience, reduced crop failure, decreased reliance on agrochemical inputs, and improved soil fertility.

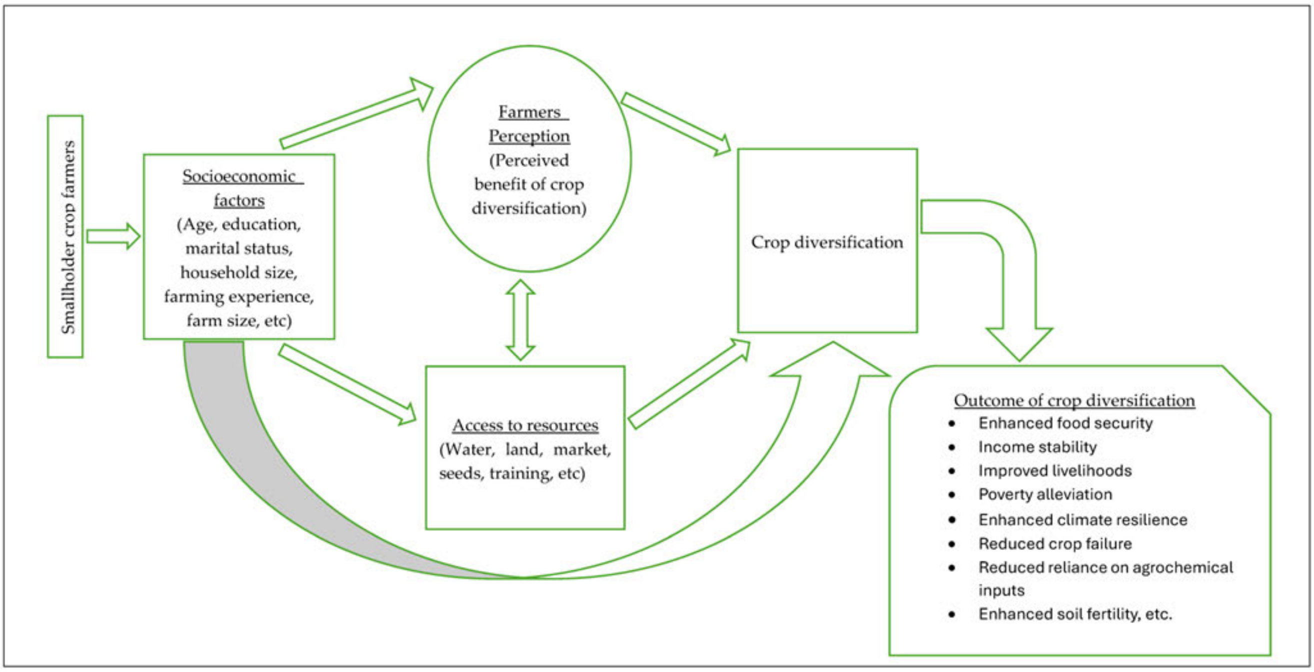

Figure 3.1: Conceptual framework for socioeconomic factors influencing crop diversification (conceived from a synthesis of reviewed models and literature). Source: Author's Concept.

3.2 Materials and methods

3.2.1 Description of the Study Area

The study was conducted in Bergville, located within the Okhahlamba Municipality of KwaZulu-Natal Province, South Africa (Figure 3.2). This site was chosen due to its location within an agroecological zone that is both ecologically diverse and agriculturally significant. Bergville forms part of South Africa's maize production belt and supports a range of agricultural activities, including livestock grazing, maize cultivation, and horticulture. It is centrally located at approximately 28°43′49.74″ S and 29°21′4.20″ E, with an altitude ranging from 1200 to 1800 m above sea level. The region experiences an average annual precipitation of 700 mm to 1,200 mm, with winter minimum temperatures ranging from 2 °C to 5 °C (occasionally accompanied by frost), and summer maximum temperatures (from December to February) ranging from 25 °C to 30 °C. This climatic variability, combined with its semi-arid conditions, makes Bergville a valuable location for studying agricultural and ecological dynamics, where rainfall and temperature fluctuations have a significant impact on local livelihoods and biodiversity. The region's water sources primarily include constructed pits, earth dams, and rainwater harvesting systems. Most smallholder farmers in Bergville rely on rainfall for irrigation, cultivating maize, vegetables, and potatoes as predominant crops. Common cropping systems include monoculture, crop rotation, and intercropping [27]. The soils are generally clay-loamy, with a high buffering capacity against pH fluctuations [28].

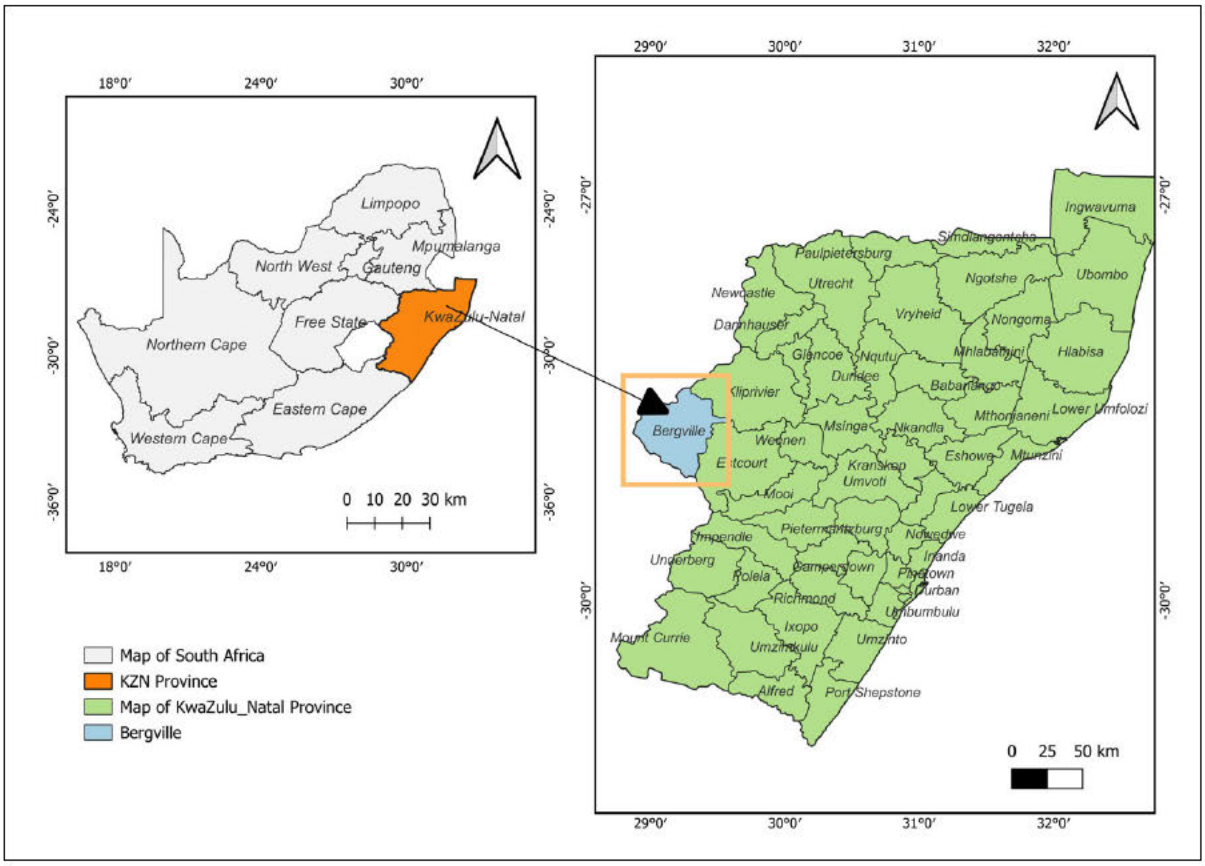

Figure 3.2: Location of Bergville in KwaZulu–Natal Province, South Africa.

3.3 Sampling Procedure and Sample Size

The study employed a quantitative research approach, incorporating a descriptive survey research design consistent with the methodology outlined by Kamarudeen [29]. As noted by Bless et al. [30], descriptive and quantitative research is instrumental in exploring beliefs, attitudes, and emerging patterns within a population. The study's target population included all farmers who were members of the Farmers' Support Group (FSG) at the time of the research, with eligibility limited to smallholder farmers specializing in crop production. The FSG's criteria were to register all resource-constrained small-holder farmers in the region with diverse farming practices and socio-economic backgrounds, ensuring inclusivity and support for a broad range of agricultural activities. A two-stage sampling procedure was employed to select respondents for the study. In the first stage, purposive sampling was used to select smallholder crop farmers from the Farmers' Support Group. In the second stage, a simple random sampling method was employed to select participants from this group, ensuring adequate representation and preserving the diversity among the smallholder crop farmers.

The total population of smallholder crop farmers comprised 269 individuals. Slovin's formula was used to determine the appropriate sample size for the study population. This method ensures the statistical neutrality of the selected samples. The formula was applied using a 95% confidence level and a 5% margin of error. Based on the computation, 161 smallholder farmers were randomly selected from five villages (Mlimeleni, Ezimbovini, KwanoKopela, Eqeleni, and Busingatha) in Bergville to participate in the study.

The following calculation illustrates the method used to determine the suitable sample size.

$$\mathrm{N} = \frac{\mathrm{N}}{1 + \mathrm{Ne}^2} = \mathrm{n} = \frac{269}{1 + 269(0.05)^2} = 161$$

where n = sample size (161); N = population size of smallholder farmers (269); e = desired margin of error (0.05).

3.3.1 Data Collection and Analysis

3.3.1.1 Baseline Survey

A structured questionnaire was developed as the primary survey instrument to elicit data for the study. Prior to the data collection process, four enumerators were trained to assist with data collection. Informed consent was obtained from all participating farmers, and participation was voluntary. Data were collected through face-to-face interviews using structured questionnaires, adhering to all protocols and ethical principles outlined in the Declaration of Helsinki. The questionnaire was face- and content-validated by field experts in agronomy to ensure relevance and applicability before data collection. This evaluation assessed its structure and relevance and examined whether the included variables were reasonable and clear. In addition, a reliability assessment was conducted through a pre-test to determine the instrument's stability and consistency in measuring the intended variables. The pre-test method was applied to 10 smallholder farmers from a village not included in the study. A reliability coefficient of r = 0.85 was obtained, which, according to established standards in the literature, indicates that the questionnaire was reliable [31]. The survey instrument comprised sections aligned with specific study objectives, assessing socioeconomic factors that influence crop diversification, predominant crops, cropping patterns and systems, farmers' knowledge of crop diversification benefits, and training attendance, understanding, and knowledge utilisation. Interviews were conducted in isiZulu, the respondents' native language, to ensure clarity and cultural relevance, thereby enhancing both communication and the reliability of responses. A total of 161 questionnaires were successfully administered across the five villages, with all participants actively engaged in smallholder farming.

3.3.1.2 Statistical Analysis

The survey data were imported from an Excel file into SPSS (Statistical Package for the Social Sciences). Variable names were systematically reviewed to ensure clarity and consistency in coding. During data cleaning, missing values were identified and ad-dressed using appropriate techniques. Outliers were detected with box plots and z-scores and were managed to preserve the dataset's integrity. Categorical variables were recoded for uniformity, with numerical codes assigned where applicable. This structured approach ensured the dataset was accurate, reliable, and ready for analysis. IBM SPSS software (version 29.0) was then used to perform descriptive statistical analyses, providing frequencies, percentages, means, and standard deviations for both continuous and categorical variables, thereby addressing the research objectives. The results were presented in tables, pie charts, and bar graphs for clarity and ease of interpretation. Additionally, multiple linear regression was employed to assess the extent of crop diversification, while the multivariate probit regression model was used to examine the socio-economic factors influencing crop diversification among smallholder farmers in Bergville, South Africa.

3.3.2 Model Specification

3.3.2.1 Inferential Statistics

The study employed a multiple linear regression model due to its ability to incorporate multiple independent or explanatory variables in predicting the outcome of a continuously measured dependent variable [32]. This model was particularly effective in analysing respondents' socioeconomic characteristics and their influence on the ex-tent of crop diversification, which was measured as a continuous variable. The extent of crop diversification was calculated as a proportion of the number of crops grown to the total number of crops that could feasibly be grown, which was six in this case. This made it suitable to be used as the dependent variable in the multiple linear regression model. The selection of this approach aligns with previous research [33–35], where multiple linear regression has been widely employed in similar contexts.

The explicit form of the model is presented as follows:

$$Y = \beta 0 + \beta 1X1 + \beta 2X2 + BnXn + e \qquad (1)$$

where:

Y represents the extent of crop diversification.

X is a vector of hypothesized explanatory variables, including farmers' socioeconomic characteristics (age, gender, marital status, educational attainment, household size, farming experience, farm size, market access, and sources of water for irrigation).

β is a vector of unknown parameters to be estimated, while e represents the independently and normally distributed random error term.

3.3.2.2 Multivariate Probit Model (MVP)

The study also utilized a multivariate probit model approach to examine the socioeconomic determinants of crop diversification in the region. In contrast to other dichotomous models, the MVP model effectively accounts for unobservable factors that influence smallholder farmers' crop diversification by permitting correlation across error terms of latent equations. The identified correlations allow for error terms that indicate positive correlation (complementarity) and negative correlation (substitutability) on crop diversification. In this study, the MVP model comprises three binary choice equations: vegetables, legumes, and cereals.

Hence, the study model is specified as:

$$P*im = \beta im + xim + \varepsilon im \ (m = 1, 2, 3) \qquad (2)$$

$$Pim \ \{1 \text{ if } P*im > 0 \text{ and } 0 \text{ otherwise}\}$$

The above equation is formulated under the assumption that a rational i-th farm household possesses a latent variable P∗im, which captures unobserved factors influencing the m-th crop diversification (m = 3 crop choices). Xim consists of exogenous variables that determine crop diversification, including the socioeconomic attributes of smallholder farmers, as detailed in Table 3.1. The coefficients βm quantify the effects of these explanatory variables on crop diversification. The error terms εim follow a multivariate normal distribution, each with a mean of zero and a variance–covariance matrix characterised by values of 1 along the diagonal and nonzero correlations among the off-diagonal elements. The socioeconomic variables included in the models are shown in Table 3.1.

Table 3.1: Summary description of the socioeconomic variables included in the regression models

Variables	Description	Variable Type
Age	1 = ≤25, 2 = 26–50, 3 = 51 years and above	Categorical
Gender	1 = male, 0 if otherwise	
Marital status	1 = unmarried, 2 = Married, 3 =Divorced, 4 = Widow (er)	Categorical

Education	1 = no formal schooling, 2 = primary school, 3 = secondary school, 4 = tertiary school	Categorical
Household size	Number of members in the household	Continuous
Farming experience	1 = 1–10 yrs, 2 = 11–20 yrs, 3 = 21–30 yrs, 4 = 31 and above years	Categorical
Farm size	1 = ≤2 ha, 2 = 3–5 ha, 6 and above hectares	Categorical
Source of seeds	1 = own production, 2 = supermarkets, 3 = other	Categorical
Market access	1 = yes, if a farmer has market access, 0 if otherwise	Categorical
Advantages of diversifying crops	1 = perceived advantages of crop diversification, 0 if otherwise	Categorical
Sources of water for irrigation	1 = irrigation, 2 = rainfed, 3 = both	Categorical

3.4 Ethical Consideration

Ethical clearance for this study was obtained from the University of KwaZulu–Natal Ethics Committee, facilitated by the School of Agricultural, Earth, and Environ-mental Sciences, under reference number HSSREC/00008179/2025 (ethical clearance approval included in Appendix A). During the administration of the questionnaires, the researcher sought informed consent from the participants, ensuring confidentiality throughout the process. The questionnaires were distributed at times and locations that were convenient for the participants. Before completing the questionnaires, participants were fully informed about the scope of the study, and their anonymity was preserved by not disclosing any personal identities. The study was conducted with a strong emphasis on participant welfare, ensuring that no harm was inflicted during the process. Furthermore, all participants were acknowledged and thanked for their valuable time and contribution to the completion of the questionnaires.

3.5 Results

3.5.1 Socioeconomic Attributes of the Smallholder Farmers

The results in Table 3.2 revealed the socio-economic attributes of the smallholder farmers in the surveyed region. The results indicated that the majority of respondents (50.3%) were between 26 and 50 years old, and 44.1% were between 51 and 60 years of age, followed by 9% of smallholder farmers who were under 25 years of age. Approximately 80.1% of the smallholder farmers were female, while males accounted for 19.9%. The marital status reveals that a significant proportion (52.8%) of the farmers were unmarried, while 36.6% were married, and only a few (9.9%) were widowed and 0.6% were divorced. The findings from Table 3.2

further reveal that 49.1% of the farmers had secondary education, 24.8% had primary education, and 20.5% had no formal education, with only a few (5.6%) of the respondents having tertiary education. A little above average (50.3%) had a household size of between 6 and 10 people, 32.2% had between 1 and 5 people, and only 17.3% had 11-plus people living together under the same roof. Also, the results revealed that 70.2% of the smallholder farmers' source of income was from welfare grants, 28% and 13% of income was from irrigated and rain-fed crop sales, respectively, 16.1% was from livestock sales, and 21.1% of the source of income was from remittance, followed by 15.5% from temporary employment and only a few (10.6%) from other sources (sewing, handicrafts, etc.). In addition, the majority (68.3%) of farmers obtained their food from supermarkets, while 31.1% produced their own food, and only a small percentage (0.6%) relied on food schemes or aid programs.

Furthermore, the results in Table 3.3 indicated that a significant proportion (85.1%) of the smallholder farmers had between 1 and 10 years of experience in farming and 8.7% had between 11 and 20 years, while 3.7% ranged between 21 and 30 years and only 2.5% had 31 and above years of farming experience. About 93.2% owned less than two hectares of land, 6.2% owned between three and five hectares, and a few (0.6%) owned six-plus hectares. The results further revealed that the majority (65.8%) of smallholder farmers relied on both rainfall and irrigation as their primary sources of water for farming. Conversely, a minority (8.7%) of the farmers relied exclusively on irrigation as the primary source of water, while 25.5% relied on rainfall. Approximately 71.4% of the farmers relied on supermarkets as a source of seeds, while 21.7% produced their own seeds, utilising seeds from previous harvests for the next planting season. Only a few farmers (6.8%) relied on alternative seed sources, such as Farmers Support Groups and the Department of Agriculture. The results also indicated that 49.7% of farmers had effortless access to seeds, while 40.4% had easy access, and 9.9% found it difficult to obtain seeds. Additionally, the majority (80.1%) of the farmers had no access to the market, while a minority (19.9%) had access to it.

Table 3.2: Distribution of the socio-economic attributes of smallholder farmers.

Socio-Economic Variables	Frequency (%)
Age (Years)	
≤25	9 (5.6)
26–50	82 (50.3)
51 and above	70 (44.1)
Gender	

Female	129 (80.1)
Male	32 (19,9)
Marital Status	
Unmarried	85 (52.8)
Married	59 (36.6)
Divorced	1 (0.6)
Widow (er)	16(9.9)
Education	
No formal schooling	33 (20.5)
Primary school	40 (24.8)
Secondary school	79 (49.1)
Tertiary school	9 (5.6)
Household Size	
1–5 people	52 (32.2)
6–10 people	81 (50.3)
11 and above	28 (17.3)
Source of income	
Temporal employment	25 (15.5)
Welfare grant	113 (70.2)
Remittances	34 (21,1)
Crop sales—irrigated	45 (28)
Crop sales—rainfed	21(13)
Livestock sales	26 (16.1)
Other	17 (10.6)
Source of food	
Own production	50 (31.1)
Purchased	110 (68.3)
Food aid	1 (0.6)

*Multiple choice response.

Table 3.3: Distribution of the socio-economic attributes of smallholder farmers contd.

Socio-Economic Variables	Frequency (%)
Years of farming experience	
1–10 yrs	137 (85.1)
11–20 yrs	14 (8.7)
21–30 yrs	6 (3.7)
31 and above	4 (2.5)
Farm size (hectares)	
≤2	150 (93.2)
3–5 ha	10 (6.2)
6 and above	1 (0.6)
Sources of water for irrigation	

Irrigation	14 (8.7)
Rainfall	41 (25,5)
Both	106 (65.8)
Sources of seeds	
Own production	35 (21.7)
Supermarkets	115 (71.4)
Other	11 (6.8)
How easy to get seeds?	
Very easy	80 (49.7)
Easy	65 (40.4)
Not easy	16 (9.9)
Market access	
Yes	32 (19.9)
No	129 (80.1)

*Multiple choice response.

3.5.2 Farming Practices Utilized by Smallholder Farmers in the Study Area

The results in Figure 3.3 present an analysis of the farming practices and cropping systems of smallholder farmers in the study area. The study found that a significant proportion (48.4%) of farmers practice intercropping, followed by 33.5% who practice monoculture (sole cropping), while 16.8% adopted crop rotation. Only a minority (1.2%) engage in relay cropping (Figure 3.3).

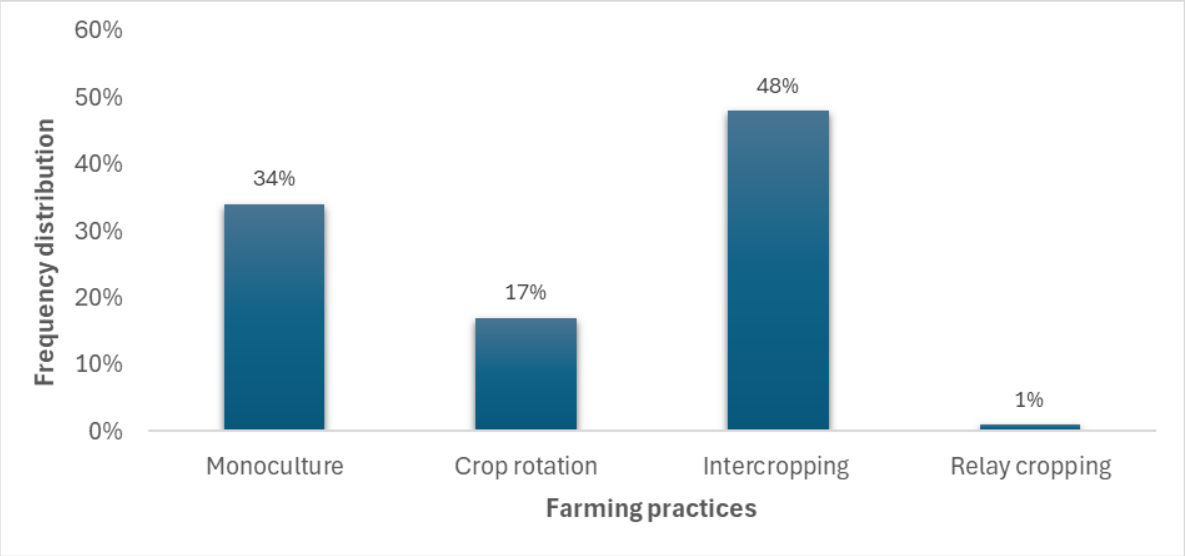

Figure 3.3: Frequency distribution of farming practices used by smallholder farmers in the study area

3.6 Crop Cultivation Patterns Among Smallholder Farmers in the Study Area

Figure 3.4 presents an analysis of crop cultivation patterns among smallholder farmers in the study area. The results indicate that vegetable cultivation is the most predominant, practiced by 87% of farmers, followed by cereals cultivation at 56%. Additionally, 43% of respondents engage in legume cultivation (Figure 3.4).

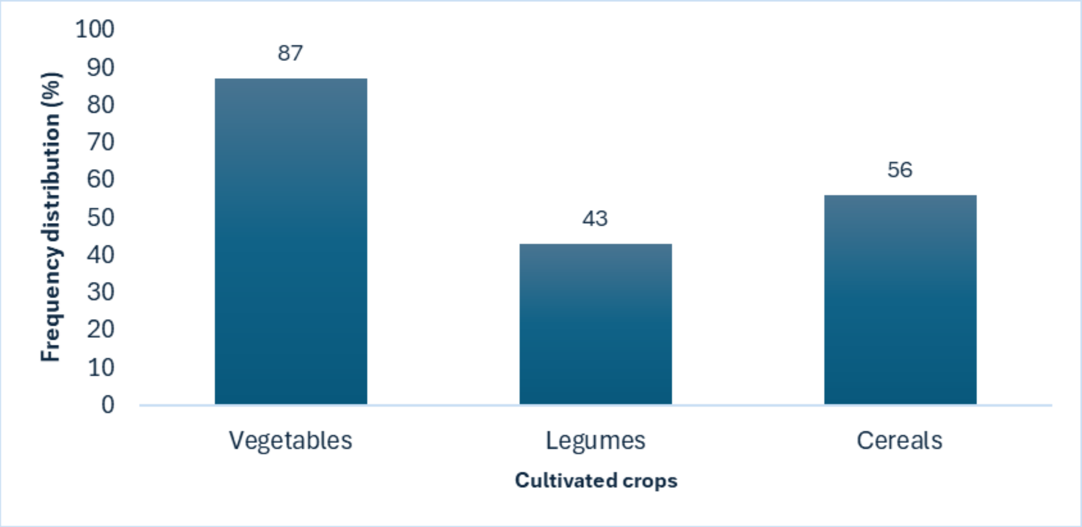

Figure 3.4: Frequency distribution of crops cultivated by smallholder farmers in the study area.

3.6.1 Smallholder Farmers' Socioeconomic Determinants of Crop Diversification

The results presented in Table 3.4 reveal the estimates of socio-economic attributes influencing the extent of crop diversification among smallholder farmers, as determined using a multiple linear regression model. The results of the multiple linear regression analysis indicated a significant relationship ($R^2 = 0.398$) between the independent variables and the extent of crop diversification. The model predicted about 40% of the variation in farmers' crop diversification, with an F-test value of 8.95 and statistical significance at $p < 0.01$. This demonstrates that the model is a good fit and confirms that the selected independent variables play a significant role in determining diversification decisions among smallholder farmers. The Variance Inflation Factor (VIF) was used to test for multicollinearity among the variables in the model, and it was discovered that multicollinearity was not a problem as the VIF value was 1.30 with a high tolerance value across the variables. The results further revealed that education level ($t = 2.46$) and household size ($t = 2.49$) were significant at $p < 0.05$, while market access ($t = 4.50$) and advantages of diversifying crops ($t = 5.79$) were highly significant at $p < 0.01$. This implies that these four variables have a significant influence on the extent of crop diversification in the region.

Table 3.4: Socio-economic determinants of crop diversification extent among smallholder farmers.

Characteristics	**Coeff.**	**Std.Err**	**T-Value**	***p* > t**	**VIF**	**Tolerance**
Age	0.060	0.104	0.58	0.562	2.02	0.494553
Gender	−0.161	0.284	−0.57	0.570	1.04	0.963210

Marital status	0.189	0.148	1.28	0.203	1.46	0.683164
Education	0.437	0.177	2.46	0.015 **	1.94	0.515743
Household size	0.079	0.032	2.49	0.014 **	1.25	0.799583
Farming experience	0.076	0.095	0.79	0.428	1.09	0.920088
Farm size	0.269	0.291	0.93	0.356	1.06	0.947418
Source of seeds	0.366	0.231	1.59	0.114	1.13	0.882091
Market access	1.335	0.297	4.50	0.000 ***	1.13	0.881867
Advantages of diversifying crops	1.616	0.279	5.79	0.000 ***	1.09	0.915646
Sources of water for irrigation	0.226	0.178	1.27	0.206	1.07	0.935039
	−0.883					
Constant	8.95					
F	0.000					
Prob > F	0.398					
R-squared	0.354					
Adj R-squared						
Mean VIF					1.30	

Note: Statistical significance *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

3.6.2 Socioeconomic Factors Influencing Crop Diversification Among Smallholder Farmers

The results in Table 3.5 show the socio-economic factors influencing crop diversification among smallholder farmers in Bergville using a multivariate probit regression model. The Wald test (chi2 (30) = 62.65, Prob > chi2 = (0.000)) is highly significant at p < 0.01, suggesting that the error terms across the crop diversification equations are correlated. The significance of this lies in the fact that applying an MVP regression model was suitable for identifying the smallholder farmers' socio-economic attributes influencing crop diversification. These significant socio-economic attributes include age, marital status (MS), farming experience (FE), farm size (FS), advantages of crop diversification (ACD), and sources of water for irrigation (SWR). The significant variables that were positively related to diversification of vegetables were ACD (p < 0.01) and SWR (p < 0.01), while age (p < 0.01), MS (p < 0.01), and FS (p < 0.01) were negatively related to vegetable diversification among the smallholder farmers in the study area. Furthermore, variables such as FE (p < 0.05), FS (p < 0.1), and ACD (p < 0.01) were positively related to legume crop diversification, while only MS (p < 0.05) and FE (p < 0.05) were positively related to cereal crop diversification.

Table 3.5: Socio-economic factors influencing crop diversification among smallholder farmers.

Characteristics	**Vegetables**		**Legumes**		**Cereals**	
	Coeff.	**Std.Err**	**Coeff.**	**Std.Err**	**Coeff.**	**Std.Err**
Age	−0.416 ***	0.155	0.107	0.085	0.140	0.083
Gender	−0.362	0.413	−0.117	0.270	0.311	0.259
Marital status	0.754 ***	0.307	0.026	0.138	0.299 **	0.141

Household size	−0.043	0.052	0.031	0.028	−0.020	0.030
Farming experience	0.204	0.183	0.219 **	0.102	0.190 **	0.093
Farm size	−0.856 ***	0.345	0.670 *	0.422	0.275	0.230
Source of seeds	0.273	0.324	−0.030	0.216	0.134	0.199
Market access	4.926	151.764	0.414	0.277	−0.160	0.264
Advantages of diversifying crops	1.039 ***	0.370	0.748 ***	0.283	−0.009	0.254
Sources of water for irrigation	0.871 ***	0.287	0.002	0.172	−0.188	0.170
Constant	−0.308	1.110627	−2.454	0.873	−1.408	0.760
N	161					
Wald chi2(30)	62.65					
Log-likelihood	−208.631					
Prob > chi2	0.000					

*, **, and *** signify statistical significance at $p < 0.1$, $p < 0.05$, and $p < 0.01$ levels, respectively.

3.6.3 Smallholder Farmers' Knowledge Level on Crop Diversification Benefits

The results in Table 3.6 revealed that the majority (50.9%) of smallholder farmers had knowledge of the potential of crop diversification to alleviate food insecurity through improving yields, while only 49.1% had limited knowledge. About 56.5% and 59% knew that crop diversification ensures production stability by providing insurance and increases farmers' economic returns (income), while 43.5% and 41.0% had no knowledge, respectively. A minority (37.9%) of farmers had knowledge of crop diversification's ability to reduce the risks associated with agricultural production (reducing pests, suppressing weeds, and disease pressure), which resulted in 62.1% having limited knowledge. In addition, only less than half (40.4%) of the farmers had knowledge of crop diversification's potential to increase the resilience of farming systems, which led to more than half (59.6%) having no knowledge. Furthermore, the results indicated that 52.2% knew that crop diversification improves crop water-use efficiency and soil fertility (55.3%), while 47.8% and 44.7% had limited knowledge, respectively.

Table 3.6: Knowledge level of smallholder farmers on crop diversification benefits.

Tested Knowledge on Crop Diversification Benefits	**Frequency (%)**	**Frequency (%)**
	Yes	**No**
a. Did you know that crop diversification alleviates food insecurity by improving yields?	82 (50.9)	79 (49.1)
b. Did you know that crop diversification ensures production stability through providing insurance (you can still rely on the other crop if one fails)?	91(56.5)	70 (43.5)
c. Did you know that crop diversification increases farmers' economic returns (income)?	95 (59.0)	66 (41.0)
d. Did you know that crop diversification reduces the risks associated with agricultural production (reduces pests and suppresses weeds and disease pressure)?	61 (37.9)	100 (62.1)

e. Did you know that crop diversification improves crop water-use efficiency?	84 (52.2)	77 (47.8)
f. Did you know that crop diversification improves soil fertility?	89 (55.3)	72 (44.7)
g. Did you know that crop diversification increases the resilience of farming systems?	65 (40.4)	96 (59.6)

3.6.4 Smallholder Farmers' Training Attendance, Understanding, and Knowledge Utilization

The findings in Table 3.7 show that smallholder farmers receive training from both the Farmers Support Group and the Department of Agriculture extension officials. About 49.7% attended all training sessions that were held by both organizations, while 50.3% only attended a few training sessions. In addition, more than half of the study population understood the information provided in the training sessions, which resulted in 45.3% lacking understanding. The results further revealed that a significant proportion (57.8%) of the farmers put into practice all the advice provided in the trainings, while 42.2% failed to practice or adopt all the advice provided in the trainings.

Table 3.7: Training attendance, understanding, and knowledge utilization among smallholder farmers in the study area.

Statement	Frequency (%) Yes	Frequency (%) No
a. Attended all training sessions that are held by the Farmers Support Group/Department of Agriculture's extension officers.	80 (49.7)	81 (50.3)
b. Fully understand the information provided in the training sessions.	88 (54.7)	73 (45.3)
c. Put into practice all the advice given in the training.	93 (57.8)	68 (42.2)

3.7 Discussion

3.7.1 Socio-Economic Attributes of the Smallholder Farmers in the Study Area

3.7.1.1 Gender and Age Dynamics in Smallholder Cropping Systems

The present study revealed significant gender disparities in smallholder cropping systems, with women comprising 80.1% of smallholder farmers engaged in crop pro-duction. The distribution of male (19.9%) and female (80.1%) farmers in this study reflects the sampled participants. However, several studies have confirmed that many smallholder farmers in Bergville are women [27,36]. This finding indicates that agricultural activities in the study region are predominantly conducted by female farmers, aligning with previous research that identified women as the primary workforce in crop production, often surpassing male participation [37,38]. This could be attributed to women's central role in maintaining food security in the Global South [39]. However, despite their substantial involvement in agriculture, women frequently face re-source constraints, particularly regarding land ownership, due to prevailing socio-cultural norms. These limitations may hinder their ability to adopt diversified cropping systems at a higher rate. In addition to gender dynamics, the study also examined age-related trends in agricultural participation. The findings indicated that only 9% of smallholder farmers were below the age of 25, whereas 44.1% were aged 51 years or older. This suggests minimal youth engagement in agriculture, as younger individuals tend to perceive farming as an occupation for older generations, a notion previously reported by Kom et al. [37] and Geza et al. [40]. Furthermore, older farmers often demonstrate a preference for traditional agricultural practices over the adoption of new crop species or diversification strategies. To ensure the sustainability of small-holder farming systems, it is crucial to foster youth participation in agriculture, particularly in crop diversification initiatives. Targeted training programs and agricultural development policies should be designed to address structural barriers limiting youth involvement in the sector. Geza et al. [40] emphasized that existing agricultural development programs inadequately tackle the systemic challenges underlying youth participation in economic activities. Therefore, the implementation of context-specific, integrated agricultural interventions is necessary to encourage meaningful youth engagement and facilitate their active role in shaping future food systems.

3.7.1.2 Household Size, Marital Status, and Their Implications for Agricultural Practices

The findings of this study indicate that the average household size among small-holder farmers ranges between six and ten individuals, suggesting relatively large family units. Due to substantial household sizes, crop diversification becomes a crucial strategy for enhancing agricultural productivity and ensuring an adequate food supply. As highlighted by Sisha [41], household size is a key determinant of food security among rural smallholder farmers, influencing both production capacity and resource allocation. Furthermore, the study revealed that a majority (52.8%) of the farmers were unmarried. This finding is consistent with research conducted in Southern Ethiopia by Gebre et al. [42], which established a strong association between marital status and household decision-making processes. Previous studies [43–45] have also demonstrated that households led by married individuals are more likely to adopt diverse crop varieties. This could be attributed to the greater access that married farmers have to agricultural networks, including extension agents and agro-input suppliers, compared to their unmarried counterparts, who primarily depend on peer-to-peer knowledge exchange as their main source of agricultural information. These findings underscore the importance of targeted agricultural policies that address household dynamics and social structures, promoting crop diversification strategies that enhance food security and sustainable farming practices among smallholder farmers.

3.7.1.3 Education Levels Among Smallholder Farmers

The findings presented in Table 3.2 further reveal that only 5.6% of smallholder farmers had attained tertiary education, while a significant proportion had no formal education. This raises concerns regarding the achievement of Sustainable Development Goal 2 (Zero Hunger), as education plays a critical role in enhancing farmers' understanding of modern agricultural practices and their capacity to adopt innovative strategies, including crop diversification. As highlighted by Adjimoti and Kwadzo [46], higher levels of education are positively associated with increased awareness and implementation of improved farming techniques. Similar findings were reported by Samim et al. [47], who found that farmers' decisions to increase the adoption of cli-mate-smart agricultural practices were influenced by their education, household family labourers, agricultural, and other factors. Limited educational attainment among smallholder farmers may, therefore, hinder the widespread adoption of diversified cropping systems, potentially affecting food security and agricultural sustainability in the region. These findings underscore the need for targeted educational interventions and extension services to enhance farmers' knowledge and facilitate the adoption of sustainable agricultural practices.

3.7.1.4 3.4.1.4. Socioeconomic Constraints and Crop Diversification Among Smallholder Farmers

The findings of this study indicate that 70.2% of smallholder farmers rely on welfare grants as their primary source of income, highlighting the dominance of elderly farmers in the crop production sector who receive government assistance aimed at supporting vulnerable populations. These findings emphasize the need for integrating crop diversification into smallholder farming systems from the outset of agricultural development strategies. As a result, farmers could incrementally enhance their crop-ping systems, optimize resource utilization, and invest in high-value crops on small plots. The study further reveals that financial constraints and limited access to critical infrastructure, particularly irrigation facilities, pose significant challenges to small-holder farmers [17,48]. Consequently, only 28% of farmers' income is derived from irrigated crop sales, while merely 8.7% of the surveyed farmers rely exclusively on irrigation as their primary water source, with the majority depending on rainfall. These findings align with Bjornlund et al. [49], who reported that Sub-Saharan Africa has the lowest irrigation development among all developing regions, with only 4% of arable land under irrigation, compared to 47% in Asia and 18% globally [50]. Due to these constraints, enhancing the productivity of existing irrigated land through crop diversification remains a viable strategy for meeting future food demands. Additionally, the study reveals that most farmers source their food from supermarkets, while only 31.1% produce their own food. This may be attributed to the limited adoption of crop diversification and the exclusion of drought-tolerant crops, which exacerbates food insecurity, a persistent challenge in Sub-Saharan Africa. However, the inclusion of a diverse range of traditional crop varieties within production systems can significantly improve resilience, enabling farming populations to better adapt to fluctuating environmental and economic conditions [45,51]. These findings highlight the importance of promoting diversified and sustainable agricultural practices to enhance food security and economic stability among smallholder farmers.

3.7.1.5 Farming Experience, Land Ownership, and Their Implications for Crop Diversification

The findings presented in Table 3.3 indicate that a significant proportion of small-holder farmers have between 1 and 10 years of farming experience. This suggests that elderly farmers, who have accumulated extensive agricultural knowledge, are more likely to engage in diversified farming. Similarly, younger farmers, being more dynamic and adaptable, may also be inclined to diversify their cropping systems to enhance productivity. These observations align with the findings of Kemboi et al. [23], who reported that farming experience can have both positive and negative associations with crop diversification, depending on various socio-economic and environmental factors. The study revealed that 93.2% of farmers owned less than two hectares of land. This finding underscores the limited access of smallholder farmers, particularly women, to agricultural resources such as land, capital, and technology when compared to their male counterparts. These results are consistent with the findings of Zakaria et al. [52], who highlighted gender disparities in access to productive agricultural assets. The restrict-ed availability of land may be attributed to multiple factors, including population growth, agricultural development pressures, land tenure policies, and broader socioeconomic and climatic conditions [17]. Addressing these constraints through policy interventions and targeted support mechanisms is essential for enhancing smallholder farmers' capacity to adopt sustainable and diversified farming practices.

3.7.1.6 Impact of Land Size, Seed Availability, and Market Access on Crop Diversification

The findings of this study suggest that the decline in land size may negatively impact crop diversification, as farmers with larger landholdings are generally more inclined and capable of cultivating a diverse range of crops [23,53]. Limited land availability restricts opportunities for crop rotation, intercropping, and the introduction of new crop varieties, thereby hindering the potential benefits of diversified farming systems. Additionally, the study revealed that only 21.7% of smallholder farmers produce their own seeds, indicating that limited seed availability may be a significant barrier to crop diversification in the region. Access to quality seeds is essential for promoting di-versified agricultural systems, and the lack thereof may contribute to low adoption rates of improved and alternative crop varieties. Furthermore, the study found that 80.1% of farmers lack access to formal markets. Market access plays a crucial role in determining smallholder farmers' ability to diversify their crops, as it influences both input availability and the profitability of diverse cropping systems. Hlatshwayo et al. [54] highlighted that limited market access is closely linked to education levels and various structural barriers that hinder smallholder farmers from engaging in commercial agriculture. In South Africa, many smallholder farmers reside in remote areas with poorly maintained roads, inadequate market infrastructure, limited transportation and storage facilities, and insufficient skills and information. These challenges contribute to high transaction costs, further discouraging market participation and affecting crop diversification efforts. Enhancing smallholder farmers' market access through infrastructure development, improved transportation networks, and capacity-building initiatives can play a pivotal role in promoting crop diversification. Strengthening market linkages and reducing barriers to entry can help farmers actively participate in diversified farming systems, ultimately contributing to food security and poverty alleviation in rural communities.

3.7.2 Farming Practices Utilized by Smallholder Farmers in the Region

The findings of this study indicate that less than half of smallholder farmers practice intercropping, primarily integrating maize (*Zea mays*) with pumpkins (*Cucurbita spp.*) or sugar beans (*Phaseolus vulgaris*), while 33.5% continue to engage in monocul-ture, predominantly maize. Only 16.8% of farmers have adopted crop rotation (Figure 3.3). These results highlight the limited adoption of crop diversification in the region, despite its well-documented benefits, including increased crop yield [55,56], reduced vulnerability to climatic shocks, improved soil fertility [57], enhanced pest and disease control, and reduced reliance on agrochemical inputs [55]. The observed low adoption rates emphasize the need for targeted interventions to promote crop diversification, particularly in smallholder farming systems in sub-Saharan Africa. Strategies should focus on improving access to training, resources, and knowledge dissemination to enhance the uptake of diversified cropping systems. These interventions must be tailored to accommodate local agronomic conditions, socio-economic factors, and prevailing challenges, as suggested by Gitari et al. [58]. The predominance of cereal monocropping suggests that many farmers remain reliant on traditional agricultural practices, with limited transition toward diversified cropping systems. This finding aligns with the conclusions of Nyamayevu et al. [59], who attributed the persistence of monoculture to factors such as limited access to high-quality seeds, labour shortages in low-input farming systems, and land constraints. Additionally, the diffusion of diversified cropping systems may be influenced by farmer-to-farmer knowledge exchange, commonly referred to as peer-to-peer extension. The lack of widespread engagement in such knowledge-sharing mechanisms has likely contributed to a significant gap in awareness, thereby impeding the broader adoption of crop diversification practices among smallholder farmers.

3.7.2.1 Crop Cultivation Patterns Among Smallholder Farmers in the Study Area

Crop production in the study area is primarily focused on vegetable cultivation, followed by cereals, while a smaller proportion of farmers engage in legume farming. Vegetable cultivation encompasses a wide range of crops, including spinach (*Spinacia oleracea*), beetroot (*Beta vulgaris*), onion (*Allium cepa*), carrot (*Daucus carota*), green pepper (*Capsicum annuum*), sweet potato (*Ipomoea batatas*), potato (*Solanum tuberosum*), chili pepper (*Capsicum spp.*), eggplant (*Solanum melongena*), and cabbage (*Brassica oleracea*). The predominant legumes grown include sugar bean (*Phaseolus vulgaris*), kidney bean (*Phaseolus vulgaris*), and cowpea (*Vigna unguiculata*). The primary cereals cultivated in the region are maize (*Zea mays*) and wheat (*Triticum aestivum*). Similar findings were reported by Ojiewo et al. [60] and Mkhize et al. [61], who highlighted that vegetable production and consumption serve as a potent mechanism for disadvantaged smallholder farmers to obtain essential nutrients in their diets while generating much-needed income through trade. This underscores the need to improve market access for other crops, such as legumes, to enhance their diversification, which plays a crucial role in diversifying farm incomes and improving dietary nutrition.

3.7.3 Socio-Economic Determinants of Crop Diversification Extent Among Smallholder Farmers

The study findings on the socio-economic determinants influencing the extent of crop diversification using a multiple linear regression model indicate that the education level of smallholder farmers was statistically significant at $p < 0.05$, with a coefficient of 0.437. This positive correlation suggests that as farmers' education levels in-crease, so does the extent of crop diversification. Educated farmers demonstrated a greater propensity to diversify their cropping systems compared to their illiterate counterparts. These findings are consistent with those of Mengistu et al. [62], who re-ported that an increase in the literacy level of household heads enhances the likelihood of household food security by 7.9%. This implies that educated farmers may expand their crop diversification efforts to achieve higher yields and stability, thereby alleviating food insecurity. Additionally, the results indicate that household size was statistically significant at $p < 0.05$, with a coefficient of 0.079. This finding suggests that household size influences the extent of crop diversification in the study region. Larger farm households typically possess a greater labour force, facilitating the timely planting of crops and mitigating delays that could be exacerbated by climate variability, as highlighted by Khan et al. [63].

A highly significant ($p< 0.01$) positive relationship was observed between farmers' perceptions of the advantages of crop diversification (coefficient = 1.616) and the ex-tent of diversification. This finding suggests that as farmers become increasingly aware of the benefits of crop diversification, they are more inclined to implement diversification strategies to a greater extent. Agricultural extension services were identified as a primary source of information for smallholder farmers. As a result, frequent interactions with extension agents are likely to enhance the adoption of improved agricultural innovations, including diversification into higher-value crops [64]. The study also revealed that market access was highly significant at $p < 0.01$, with a positive coefficient of 4.926. This finding indicates that market access plays a crucial role in influencing the extent of crop diversification. As market accessibility improves, farmers are increasingly motivated to diversify their crop production within the region. These results highlight the importance of enhancing education, extension services, and market access as key strategies for promoting sustainable crop diversification extent among smallholder farmers.

3.7.4 Socio-Economic Factors Influencing Crop Diversification Among Smallholder Farmers

The results of this study indicate that socio-economic factors, including age, marital status (MS), farming experience (FE), farm size (FS), perceived advantages of crop diversification (ACD), and sources of water for irrigation (SWR), significantly influence crop diversification among smallholder farmers. Using a multivariate probit regression model, MS, ACD, and SWR were found to be highly significant at $p < 0.01$, demonstrating positive correlations of 0.754, 1.039, and 0.871, respectively, with vegetable crop diversification. These findings suggest that an increase in water sources for irrigation and perceived benefits of crop diversification enhances the adoption of vegetable diversification. Additionally, marital status strongly influenced farmers' decisions regarding vegetable diversification in the study area. The increased knowledge and adoption of vegetable diversification in the region may be attributed to training programs and the provision of vegetable seedlings and seeds by the Farmers Support Group. During interviews, farmers reported cultivating up to six or more vegetable varieties in a small piece of land. Commonly produced vegetables included spinach, cabbage, carrots, beetroot, onions, green peppers, chilies, potatoes, tomatoes, and eggplant. Furthermore, findings revealed that farmers with access to reliable water sources were more inclined to produce a greater variety of vegetables compared to those reliant solely on rainfall. This supports the hypothesis that crop diversity de-clines with decreasing water availability. The results align with the findings of Harri-son et al. [65], who posited that water is a key limiting factor in arid and semi-arid ecosystems, shaping plant diversity and primary productivity. Moreover, the influence of marital status on vegetable diversification may be attributed to the necessity for food security among unmarried farmers, who constituted a dominant demographic in the study area. In contrast, a study by Lemma and Sharma [66] reported that married women are more committed to ensuring a stable food supply and prioritize household well-being compared to their unmarried counterparts. The observed differences may be due to the focus of Lemma and Sharma [66] on urban agricultural settings, whereas the present study is based on rural agricultural communities.

The findings of this study further indicate that both age and farm size (FS) exhibit a statistically significant negative correlation with vegetable diversification, as evidenced by their correlation coefficients of −0.416 and −0.856, respectively ($p < 0.01$). This negative correlation implies that an increase in one variable corresponds with a decrease in the other. The results suggest that age plays a critical role in determining the extent of crop diversification, aligning with the conclusions of Inoni et al. [64]. Older farmers may be less inclined to diversify their crops due to factors such as risk aversion, adherence to traditional farming practices, physical constraints (e.g., declining strength), and a reduced propensity to adopt innovative agricultural techniques. Furthermore, the observed inverse relationship between FS and vegetable diversification may be attributed to larger farms prioritizing monoculture over diversified vegetable production. This could be due to their access to agricultural inputs, which facilitate the practice of monoculture farming. These findings are consistent with the results of Mortensen and Smith [67], who argued that farmers can effectively cultivate crops in monocultures or simplified crop rotations due to the availability of synthetic fertilizers and pesticides. As a result, continuous monoculture systems would not be viable without such chemical inputs. Moreover, the study findings indicate that farmers' experience (FE) ($p < 0.05$), farm size (FS) ($p < 0.1$), and awareness of crop diversification (ACD) ($p < 0.01$) exhibit statistically significant positive correlations with legume crop diversification, as reflected in their respective correlation coefficients of 0.219, 0.670, and 0.748. These results suggest that as these factors increase, the level of legume crop diversification also increases, implying that more experienced farmers demonstrate a slightly higher propensity to diversify their legume crops. Interactive interviews with farmers further revealed that sugar bean (common bean) is the most extensively cultivated legume in the region, followed by kidney bean and cowpea, to a lesser extent. Additionally, larger farm sizes were associated with greater legume crop diversification, aligning with the findings of Inoni et al. [64], who noted that increased farm size enhances farmers' willingness and capacity to engage in crop diversification. The probability of adopting diversified cropping systems increases as land availability expands, highlighting agricultural land as a crucial production factor in rural livelihoods. Moreover, farmers who perceive greater benefits from legume crop diversification are more likely to engage in diverse cropping practices. However, field observations indicate a persistent lack of awareness and unfavourable attitudes toward legume crop diversification among farmers. These findings underscore the necessity of enhancing farmers' knowledge and perceptions regarding diversified legume cultivation, as recommended by Lema et al. [68] and Marie et al. [69], to facilitate greater adaptation to climate variability. Furthermore, the results indicate that only marital status (MS) ($p < 0.05$) and FE ($p < 0.05$) show statistically significant positive correlations with cereal crop diversification, particularly maize, with correlation coefficients of 0.299 and 0.190, respectively. This finding suggests that marital status may influence diversification decisions, as married farmers often face increased household responsibilities and financial demands, incentivizing them to adopt diversification as a risk management strategy. Moreover, married individuals may have better access to la-bour, as family members contribute to farming activities. Experienced farmers, on the other hand, are more likely to possess a comprehensive understanding of market dynamics, climate variability, and soil suitability, thereby enabling them to implement diverse cropping strategies to enhance productivity and mitigate agricultural risks.

3.7.5 Smallholder Farmers' Knowledge Level on Crop Diversification Benefits

The findings of this study indicate that a significant proportion of smallholder farmers (49.1%) have limited knowledge regarding the potential benefits of crop diversification in mitigating food insecurity through enhanced agricultural yields. About 56.5% of the respondents recognized that crop diversification contributes to production stability by providing insurance against crop failure and increasing farmers' eco-nomic returns. In addition, only 37.9% of farmers were aware of crop diversification's role in reducing agricultural production risks, such as pest infestations, weed suppression, and disease pressure. This lack of awareness highlights a significant gap in knowledge dissemination and extension services, which may have contributed to the low adoption rates of diversified cropping systems in the region. Moreover, only 40.4% of farmers understood the potential of crop diversification to enhance the resilience of farming systems, while the majority lacked knowledge of its role in improving water-use efficiency and soil fertility. These findings suggest that many smallholder farmers could not fully comprehend the agronomic and economic advantages associated with diversification. Limited awareness could be attributed to restricted access to agricultural extension services, a lack of formal agricultural education, or a strong reliance on traditional monocropping practices. The implications of these findings underscore the need for targeted interventions aimed at enhancing farmers' knowledge of diversification strategies. Strengthening agricultural extension programs, implementing farmer training workshops, and promoting participatory learning approaches could facilitate knowledge transfer and encourage broader adoption of crop diversification. These findings align with previous research [66,69], which emphasizes the critical role of education and extension services in influencing farmers' decisions to adopt diversified cropping systems. Addressing this knowledge gap among smallholder farmers is essential for fostering a more resilient and sustainable agricultural sector, particularly in the context of climate change and fluctuating market conditions.

3.7.6 Smallholder Farmers' Training Attendance, Understanding, and Knowledge Utilization

The study results indicate that smallholder farmers receive agricultural training from both the Farmers Support Group and the Department of Agriculture. Approximately 49.7% of farmers reported attending all training sessions conducted by these organizations, whereas 50.3% participated in only a limited number of sessions. This suggests a relatively balanced distribution in training attendance, with a significant proportion of farmers not fully engaging in the available capacity-building initiatives. The study findings further revealed that more than half of the study population demonstrated an adequate understanding of the information provided during the training sessions. However, 45.3% of the farmers reported difficulties in comprehending the training content, which could hinder the effective application of the knowledge imparted. This gap in understanding could be attributed to factors such as the complexity of training materials, language barriers, or variations in educational backgrounds among farmers. In addition, the study found that 57.8% of farmers implemented the recommendations provided during training sessions, while 42.2% either partially adopted or failed to implement the advised agricultural practices. This variation in adoption rates could be influenced by constraints such as limited access to necessary resources, financial constraints, or resistance to change due to entrenched traditional farming practices. Therefore, these findings underscore the need for enhanced training methodologies that consider farmers' diverse educational backgrounds and learning capacities [70]. Strengthening the effectiveness of training programs through interactive and practical learning approaches, follow-up support, and tailored extension services could improve comprehension and encourage higher adoption rates of recommended agricultural practices as reported by Mbesa et al. [71]. Addressing these challenges is crucial for maximizing the impact of training initiatives on smallholder farmers' productivity and overall agricultural sustainability.

3.8 Conclusion, Recommendations, and Future Directions

This study assessed the socioeconomic factors influencing crop diversification among smallholder farmers in South Africa, using the KwaZulu-Natal Province as a case study. Farmers in the study area practice crop diversification. However, the findings indicate that socioeconomic factors play a crucial role in shaping diversification decisions within smallholder farming systems. In line with previous research, this study confirms that limited access to land, water availability, market access, and education level constrain farmers' ability to diversify their crop choices. Marital status, household size, farming experience, perceived advantages of crop diversification, and limited technical knowledge further influence crop diversification. Additionally, older farmers were less likely to diversify due to risk aversion, adherence to traditional farming practices, physical limitations, and reluctance to adopt innovative agricultural techniques. To address these challenges, the study recommends promoting youth engagement in agriculture, particularly in crop diversification initiatives, by fostering their active role in shaping future food systems. This can be achieved through targeted training programs and policies that address structural barriers limiting youth participation. Integrating crop diversification awareness into local policies and development programs could contribute to more sustainable farming systems, enhancing food security.

Despite the promising results of this study, it is essential to acknowledge that, like other research studies, this article has limitations. The study specifically focused on smallholder crop farmers in Bergville. This may introduce some bias, as the sample comprised crop farmers affiliated with the Farmers Support Group in the region. However, this study attempted to mitigate bias by using a multistage sampling strategy to ensure representation of diverse demographic groups, particularly re-source-constrained farmers actively engaged in various farming practices. Moreover, the study employed techniques to enhance data accuracy and reliability, including the use of multiple question formats to capture comprehensive information and minimize response errors. Despite these limitations, the study provides valuable insights for policymakers and contributes to a more profound understanding of how socioeconomic factors influence crop diversification among resource-constrained farmers in rural communities of the Global South. Based on the outcomes of this study, future studies should examine the long-term impact of crop diversification on farm productivity, in-come stability, and resilience to climate change. Additionally, research should explore the role of digital technologies, climate-smart agriculture, and financial incentives in influencing crop diversification decisions. A gender-focused approach is also crucial to better understand how social and economic disparities affect diversification outcomes. Furthermore, longitudinal studies assessing the effectiveness of policy interventions and farmer training programs could provide deeper insights into strategies for enhancing diversification practices among smallholder farmers.

References

1. Fan, S.; Rue, C. The role of smallholder farms in a changing world. In The Role of Smallholder Farms in Food and Nutrition Security; Springer: Cham, Switzerland, 2020; pp. 13-28.

2. Dixon, J.; Garrity, D.; Boffa, J.; Williams, T.O.; Amede, T.; Auricht, C.; Lott, R.; Mburathi, G. Farming systems and food security in Africa. In Priorities for Science and Policy Under Global Change; Dixon, J., Garrity, D.P., Boffa, J.-M., Williams, T.O., Amede, T., Auricht, C., Lott, R., Mburathi, G., Eds.; Routledge: New York, NY, USA, 2020.

3. Kapari, M.; Hlophe-Ginindza, S.; Nhamo, L.; Mpandeli, S. Contribution of smallholder farmers to food security and opportunities for resilient farming systems. Front. Sustain. Food Syst. 2023, 7, 1149854.

4.Touch, V.; Tan, D.K.; Cook, B.R.; Li Liu, D.; Cross, R.; Tran, T.A.; Utomo, A.; Yous, S.; Grunbuhel, C.; Cowie, A. Smallholder farmers' challenges and opportunities: Implications for agricultural production, environment and food security. J. Environ. Manag. 2024, 370, 122536.

5. Antwi-Agyei, P.; Stringer, L.C. Improving the effectiveness of agricultural extension services in supporting farmers to adapt to climate change: Insights from northeastern Ghana. Clim. Risk Manag. 2021, 32, 100304.

6. Mutengwa, C.S.; Mnkeni, P.; Kondwakwenda, A. Climate-smart agriculture and food security in southern Africa: A review of the vulnerability of smallholder agriculture and food security to climate change. Sustainability 2023, 15, 2882.

7. Antonelli, C.; Coromaldi, M.; Pallante, G. Crop and income diversification for rural adaptation: Insights from Ugandan panel data. Ecol. Econ. 2022, 195, 107390.

8. Barman, A.; Saha, P.; Patel, S.; Bera, A. Crop diversification an effective strategy for sustainable agriculture development. Sustain. Crop Prod. Recent Adv. 2022. DOI: 10.5772/intechopen.102635.

9. Zou, Y.; Liu, Z.; Chen, Y.; Wang, Y.; Feng, S. Crop rotation and diversification in China: Enhancing sustainable agriculture and resilience. Agriculture 2024, 14, 1465.

10. Rayns, F.; Conroy, J.; Smith, B. Using legumes as a source of fertility in protected cropping systems. In TRUE-Project Case Studies E-book: Facilitating Home-Grown Legumes as the Foundation of Sustainable Food- and Feed-Systems; The James Hutton Institute: Dundee, UK, 2021, pp. 52–54.

11. Mihrete, T.B.; Mihretu, F.B. Crop Diversification for Ensuring Sustainable Agriculture, Risk Management and Food Security. Glob. Chall. 2025, 9, 2400267.

12. Garamu, T.; Tashome, T. Crop Diversification and Specialization: Drivers, Impacts on Climate Change Mitigation and Food Security of Small Holder Farmers in Ethiopia. Glob. Res. Environ. Sustain. 2023, 1, 37–46.

13. Tsumbu, J. Assessing the Economic Viability of Climate-Resilient Crop Varieties for Smallholder Farmers in Sub-Saharan Africa. J. Dimens. Manag. Public Sect. 2024, 5, 1–12.

14. Shikwambana, S.; Malaza, N.; Ncube, B. Enhancing the resilience and adaptive capacity of smallholder farmers to drought in the Limpopo Province, South Africa. Conservation 2022, 2, 435-449.

15. Rivera-Padilla, A. Crop choice, trade costs, and agricultural productivity. J. Dev. Econ. 2020, 146, 102517.

16. Fujimoto, T.; Suzuki, A. Different strategies of crop diversification between poor and non-poor farmers: Concepts and evidence from tanzania. Ecol. Econ. 2025, 227, 108369.

17. Acevedo, M.; Pixley, K.; Zinyengere, N.; Meng, S.; Tufan, H.; Cichy, K.; Bizikova, L.; Isaacs, K.; Ghezzi-Kopel, K.; Porciello, J. A scoping review of adoption of climate-resilient crops by small-scale producers in low-and middle-income countries. Nat. Plants 2020, 6, 1231–1241.

18. Bernzen, A.; Sohns, F.; Jia, Y.; Braun, B. Crop diversification as a household livelihood strategy under environmental stress. Factors contributing to the adoption of crop diversification in shrimp cultivation and agricultural crop farming zones of coastal Bangladesh. Land Use Policy 2023, 132, 106796.

19. Zenda, M.; Rudolph, M. A systematic review of agroecology strategies for adapting to climate change impacts on smallholder crop farmers' livelihoods in South Africa. Climate 2024, 12, 33.

20. Addicott, J.E. The Precision Farming Revolution: Global Drivers of Local Agricultural Methods; Palgrave Macmillan: Singapore, 2020.

21. Shaffril, H.A.M.; Samah, A.A.; Samsuddin, S.F.; Ahmad, N.; Tangang, F.; Sidique, S.F.A.; Rahman, H.A.; Burhan, N.A.S.; Shah, J.A.; Khalid, N.A. Diversification of agriculture practices as a response to climate change impacts among farmers in low-income countries: A systematic literature review. Clim. Serv. 2024, 35, 100508.

22. Makate, C.; Wang, R.; Makate, M.; Mango, N. Crop diversification and livelihoods of smallholder farmers in Zimbabwe: Adaptive management for environmental change. SpringerPlus 2016, 5, 1135.

23. Kemboi, E.; Muendo, K.; Kiprotich, C. Crop diversification analysis amongst smallholder farmers in Kenya (empirical evidence from Kamariny ward, Elgeyo Marakwet County). Cogent Food Agric. 2020, 6, 1834669.

24. Tacconi, F.; Waha, K.; Ojeda, J.J.; Leith, P. Drivers and constraints of on-farm diversity. A review. Agron. Sustain. Dev. 2022, 42, 2.

25. Duale, M.M. Challenges and Opportunities of Livelihood Diversification in Ethiopia: A Review Article. Int. J. Agric. Econ 2024, 9, 134–147.

26. Sharma, G.; Shrestha, S.; Kunwar, S.; Tseng, T.-M. Crop diversification for improved weed management: A review. Agriculture 2021, 11, 461.

27. Vilakazi, B.S.; Zengeni, R.; Mafongoya, P. Indigenous strategies used by selected farming communities in KwaZulu Natal, South Africa, to manage soil, water, and climate extremes and to make weather predictions. Land Degrad. Dev. 2019, 30, 1999–2008.

29. Kamaruddeen, A.M. Determinants of emerging technology adoption for safety among construction businesses. Acad. Strateg. Manag. J. 2022, 21 ,1–20.

30. Bless, C.; Higson-Smith, C.; Kagee, A. Fundamentals of Social Research Methods: An African Perspective; Juta and Company Ltd.: Cape Town, South Africa, 2006.

31. Mulaudzi, A.I.; Olorunfemi, O.D.; Agholor, A.I. Social media utilization level among South African smallholder farmers: A case study of Mopani District, Limpopo Province. Cogent Soc. Sci. 2024, 10, 2356722.

32. Nyawo, P.H.; Olorunfemi, O.D. Perceived effectiveness of agricultural cooperatives by smallholder farmers: Evidence from a micro-level survey in north-eastern South Africa. Sustainability 2023, 15, 10354.

33. Mandal, R.; Bezbaruah, M. Diversification of cropping pattern: Its determinants and role in flood affected agriculture of Assam Plains. Indian J. Agric. Econ. 2013, 68, 169–181.

34. Sichoongwe, K. Determinants and Extent of Crop Diversification among smallholder farmers in Southern Zambia.Master’s Thesis. University of Malawi, Zomba, Malawi, 2014.

35. Douyon, A.; Worou, O.N.; Diama, A.; Badolo, F.; Denou, R.K.; Touré, S.; Sidibé, A.; Nebie, B.; Tabo, R. Impact of crop diversification on household food and nutrition security in southern and central Mali. Front. Sustain. Food Syst. 2022, 5, 751349.

36. Walker, N.; Schulze, R. An assessment of sustainable maize production under different management and climate scenarios for smallholder agro ecosystems in KwaZulu-Natal, South Africa. Phys. Chem. Earth Parts A/B/C 2006, 31, 995–1002.

37. Kom, Z.; Nethengwe, N.; Mpandeli, N.; Chikoore, H. Determinants of small-scale farmers' choice and adaptive strategies in response to climatic shocks in Vhembe District, South Africa. GeoJournal 2022, 87, 677–700.

38. Sithole, A.; Olorunfemi, O.D. The Adoption of Sustainable Farming Practices by Smallholder Crop Farmers: Micro-Level Evidence from North-Eastern South Africa. Agriculture 2024, 14, 2370.

39. Glazebrook, T.; Noll, S.; Opoku, E. Gender matters: Climate change, gender bias, and women's farming in the global South and North. Agriculture 2020, 10, 267.

40. Geza, W.; Ngidi, M.; Ojo, T.; Adetoro, A.A.; Slotow, R.; Mabhaudhi, T. Youth participation in agriculture: A scoping review. Sustainability 2021, 13, 9120.

41. Sisha, T.A. Household level food insecurity assessment: Evidence from panel data, Ethiopia. Sci. Afr. 2020, 7, e00262.

42. Gebre, G.G.; Isoda, H.; Amekawa, Y.; Nomura, H. Gender differences in the adoption of agricultural technology: The case of improved maize varieties in southern Ethiopia. Women's Stud. Int. Forum 2019, 76, 102264.

43. Kaliba, A.R.; Mazvimavi, K.; Gregory, T.L.; Mgonja, F.M.; Mgonja, M. Factors affecting adoption of improved sorghum varieties in Tanzania under information and capital constraints. Agric. Food Econ. 2018, 6, 1–21.

44. Umar, S.; Musa, M.; Kamsang, L. Determinants of adoption of improved maize varieties among resource-poor households in Kano and Katsina States, Nigeria. J. Agric. Ext. 2014, 18, 196–205.

45. Atube, F.; Malinga, G.M.; Nyeko, M.; Okello, D.M.; Alarakol, S.P.; Okello-Uma, I. Determinants of smallholder farmers' adaptation strategies to the effects of climate change: Evidence from northern Uganda. Agric. Food Secur. 2021, 10, 1–14.

46. Adjimoti, G.O.; Kwadzo, G.T.-M. Crop diversification and household food security status: Evidence from rural Benin. Agric. Food Secur. 2018, 7, 1–12.

47. Samim, S.A.; Deng, X.; Li, Z. Climate-smart agricultural practices-determinants and impact on crop production. New insights from Afghanistan. Mitig. Adapt. Strateg. Glob. Change 2024, 29, 1–31.

48. Balana, B.B.; Oyeyemi, M.A. Agricultural credit constraints in smallholder farming in developing countries: Evidence from Nigeria. World Dev. Sustain. 2022, 1, 100012.

49. Bjornlund, H.; van Rooyen, A.; Stirzaker, R. Profitability and productivity barriers and opportunities in small-scale irrigation schemes. Int. J. Water Resour. Dev. 2017, 33, 690–704.

50. You, L.; Ringler, C.; Wood-Sichra, U.; Robertson, R.; Wood, S.; Zhu, T.; Nelson, G.; Guo, Z.; Sun, Y. What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach. Food Policy 2011, 36, 770–782.

51. Vernooy, R. Does crop diversification lead to climate-related resilience? Improving the theory through insights on practice. Agroecol. Sustain. Food Syst. 2022, 46, 877–901.

52. Zakaria, H. The drivers of women farmers' participation in cash crop production: The case of women smallholder farmers in Northern Ghana. J. Agric. Educ. Ext. 2017, 23, 141–158.

53. Michler, J.D.; Josephson, A.L. To specialize or diversify: Agricultural diversity and poverty dynamics in Ethiopia. World Dev. 2017, 89, 214–226.

54. Hlatshwayo, S.I.; Ngidi, M.; Ojo, T.; Modi, A.T.; Mabhaudhi, T.; Slotow, R. A typology of the level of market participation among smallholder farmers in South Africa: Limpopo and Mpumalanga Provinces. Sustainability 2021, 13, 7699.

55. Li, C.; Hoffland, E.; Kuyper, T.W.; Yu, Y.; Zhang, C.; Li, H.; Zhang, F.; van der Werf, W. Syndromes of production in intercropping impact yield gains. Nat. Plants 2020, 6, 653–660.

56. Stratton, A.E.; Comin, J.J.; Siddique, I.; Zak, D.R.; Filipini, L.D.; Lucas, R.R.; Blesh, J. Assessing cover crop and intercrop performance along a farm management gradient. Agric. Ecosyst. Environ. 2022, 332, 107925.

57. Mazzafera, P.; Favarin, J.L.; Andrade, S.A.L.d. Intercropping systems in sustainable agriculture. Frontiers 2021, 5, 634361.

58. Gitari, H.I.; Nyawade, S.O.; Kamau, S.; Karanja, N.N.; Gachene, C.K.; Raza, M.A.; Maitra, S.; Schulte-Geldermann, E. Revisiting intercropping indices with respect to potato-legume intercropping systems. Field Crops Res. 2020, 258, 107957.

59. Nyamayevu, D.; Nyagumbo, I.; Chiduwa, M.; Liang, W.; Li, R. Understanding crop diversification among smallholder farmers: Socioeconomic insights from central Malawi. Sustainability 2024, 16, 9078.

60. Ojiewo, C.; Keatinge, D.J.; Hughes, J.; Tenkouano, A.; Nair, R.; Varshney, R.; Siambi, M.; Monyo, E.; Ganga-Rao, N.; Silim, S. The role of vegetables and legumes in assuring food, nutrition, and income security for vulnerable groups in Sub-Saharan Africa. World Med. Health Policy 2015, 7, 187–210.

61. Mkhize, X.; Oldewage-Theron, W.; Napier, C.; Duffy, K.; Mthembu, B.E. Introducing grain legumes for crop diversification and sustainable food production systems amongst urban small-holder farmers: A food and nutrition security project in KwaZulu-Natal, South Africa. Agroecol. Sustain. Food Syst. 2022, 46, 791–814.

62. Mengistu, D.D.; Degaga, D.T.; Tsehay, A.S. Analyzing the contribution of crop diversification in improving household food security among wheat dominated rural households in Sinana District, Bale Zone, Ethiopia. Agric. Food Secur. 2021, 10, 1–15.

63. Khan, I.; Lei, H.; Shah, I.A.; Ali, I.; Khan, I.; Muhammad, I.; Huo, X.; Javed, T. Farm households’ risk perception, attitude and adaptation strategies in dealing with climate change: Promise and perils from rural Pakistan. Land Use Policy 2020, 91, 104395.

64. Inoni, O.E.; Gani, B.S.; Sabo, E. Drivers of crop diversification: Evidence from smallholder farmers in Delta State Nigeria. Acta Univ. Agric. Et Silvic. Mendel. Brun. 2021, 69, 59–70.

65. Harrison, S.; Spasojevic, M.J.; Li, D. Climate and plant community diversity in space and time. Proc. Natl. Acad. Sci. USA 2020, 117, 4464–4470.

66. Lemma, T.; Sharma, M. Motivations for women’s participation in urban agriculture: A multivariate probit model analysis. Int. J. Agric. Sustain. 2024, 22, 2379893.

67. Mortensen, D.A.; Smith, R.G. Confronting barriers to cropping system diversification. Front. Sustain. Food Syst. 2020, 4, 564197.

68. Lema, C.F.; Kadigi, M.; Kayunze, K.A. Farmers’ Awareness of and Attitude towards Diversified Legumes Production in Singida Region, Tanzania. Eur. J. Agric. Food Sci. 2024, 6, 11–18.

69. Marie, M.; Yirga, F.; Haile, M.; Tquabo, F. Farmers’ choices and factors affecting adoption of climate change adaptation strategies: Evidence from northwestern Ethiopia. Heliyon 2020, 6, e03867.

70. Wonde, K.M.; Tsehay, A.S.; Lemma, S.E. Training at farmers training centers and its impact on crop productivity and households’ income in Ethiopia: A propensity score matching (PSM) analysis. Heliyon 2022, 8, e09837.

71. Mbesa, B.; Makindara, J.; Kadigi, M.; Majubwa, R.; Madege, R. Effect of training on knowledge, attitude, and practice on the use of hermetic storage technologies among smallholder farmers in Tanzania. Afr. J. Empir. Res. 2024, 5, 881–893.

Chapter 4: Socioeconomic Factors Influencing Smallholder Farmers' Willingness to Cultivate Neglected Legumes and Their Selection of Suitable Planting Dates

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Abstract

Neglected legumes are fundamental to global food systems, contributing to agricultural sustainability, enhancing food security, and strengthening the resilience of smallholder farming systems. However, they remain underutilized and have historically received limited attention in terms of cultivation, research, and market development, despite their significant nutritional, agronomic, and environmental potential. This study assessed socioeconomic factors influencing farmers’ willingness to cultivate neglected legumes and their selection of suitable planting dates in Bergville, South Africa. A simple random sampling procedure was employed to collect data from 150 farmers specializing exclusively in crop production. An action research design was implemented, comprising structured training sessions on neglected legumes and trial demonstrations. Data were collected through a structured survey questionnaire, focus group discussions, and key informant interviews. Common bean (*Phaseolus vulgaris*) is widely cultivated by smallholder farmers in the region. Descriptive statistics were employed to summarize the data, while a multivariate probit model was used to identify the socioeconomic factors influencing farmers’ willingness to cultivate neglected legumes including Bambara groundnut (*Vigna subterranea*), cowpea (*Vigna unguiculata*), and pigeon pea (*Cajanus cajan*), as well as common bean (Phaseolus vulgaris), and their selection of suitable planting dates.

Findings confirmed that the majority of smallholder farmers primarily focus on vegetable cultivation, followed by cereals, while a smaller proportion engage in legume farming. The results also revealed that limited knowledge and resources, along with the lack of training programs and extension services specifically targeting neglected legumes, are significant barriers hindering their adoption and cultivation in the region. Furthermore, the study showed that a majority of smallholder farmers had never participated in legume production training. Additionally, marital status, farm size, market access, and water sources for irrigation were significant socioeconomic factors influencing farmers' willingness to cultivate neglected legumes, while household size, participation in legume training, and water sources for irrigation had a significant effect on farmers' selection of suitable planting dates. These findings underscore the need for targeted interventions, including tailored training programs, improved access to resources, and enhanced extension services, to overcome these barriers and promote the adoption of neglected legumes into smallholder farmers' cropping systems.

Keywords: legumes adoption, sustainable agriculture, farming systems, training programs, multivariate probit regression model, socioeconomic factors

4.1 Introduction

In the context of escalating global challenges such as climate change and population growth, the development and maintenance of resilient cropping systems are critical for ensuring the long-term sustainability of smallholder agriculture, enhancing food security, and improving rural livelihoods (Wijerathna-Yapa and Pathirana, 2022; Danquah et al., 2025). According to Dixon et al. (2020), cropping systems constitute the foundation of smallholder agricultural production, playing a pivotal role in food security, income generation, and environmental sustainability. These systems encompass the selection, spatial arrangement, and temporal rotation of crops within a given agricultural landscape, thereby ensuring a stable and diverse supply of food for household consumption and market sales (Nkansah-Dwamena, 2024). For smallholder farmers, well-structured cropping systems are essential in meeting dietary needs by providing access to various nutrient-dense crops, thereby contributing to food security at both the household and community levels (Pradhan et al., 2021; Mrabet, 2023). These systems are integral to sustaining rural livelihoods, as smallholder farmers often depend on their agricultural output as their primary source of income. The adoption of diversified cropping strategies enables farmers to mitigate risks associated with market volatility, pest infestations, and climate variability, thereby strengthening their economic resilience (Rosa-Schleich, 2023; Mihrete and Mihretu, 2025). Moreover, sustainable cropping systems contribute to environmental health by enhancing soil fertility, reducing erosion, and promoting biodiversity (Saliu et al., 2023). In particular, the integration of neglected legumes into cropping systems has been shown to improve soil nutrient balance and support ecological sustainability (Kebede, 2020). Given these multifaceted benefits, the promotion of resilient and diversified cropping systems is essential for advancing smallholder agriculture in the face of increasing global challenges.

The term 'neglected legumes' refers to legume species that have been underutilized or overlooked in mainstream agricultural systems, despite their significant potential to contribute to food security, nutrition, and sustainable agricultural practices. According to the Food and Agriculture Organization (FAO) (2017), neglected legumes are primarily grown in subsistence farming systems and are often overshadowed by more commercially viable crops. These species, also known as orphan crops, have historically received limited attention in terms of cultivation, research, and market development, despite their considerable nutritional, agronomic, and environmental benefits (Abberton et al., 2022; Odeku et al., 2024). These legumes are often indigenous or regionally cultivated but have not achieved widespread commercial recognition compared to major legumes such as soybeans or peanuts. As noted by

DALRRD (2020), data on the area and production of neglected legumes in Bergville, South Africa, remain limited. However, soybeans continue to be a significant legume crop in the region, with approximately 9,929 hectares under cultivation and a total production of 52,990 metric tons. Dry beans follow with a production volume of 900 tons, accounting for only 1.3% of the national output.

However, the neglected legumes offer a range of agronomic and nutritional benefits, making them valuable components of sustainable agricultural systems, particularly within smallholder farming systems. As previously discussed in the review, chapter 2, neglected legumes are recognized for their high nutritional value and potential contribution to food and nutrition security (Vilakazi et al., 2025). Their diverse nutritional profile positions them as an important source of plant-based nutrition for populations facing dietary deficiencies. Neglected legumes further contribute significantly to soil health and environmental sustainability (Samal et al., 2023). Their ability to fix atmospheric nitrogen enhances soil fertility, reducing the dependence on synthetic fertilizers and promoting sustainable soil management. These legumes exhibit resilience to pests, diseases, and drought, making them well-suited for cultivation in regions characterized by erratic rainfall and prolonged dry spells (Hossain et al., 2021; Sharma et al., 2024). Their capacity to withstand both biotic and abiotic stresses enhances their reliability in ensuring stable yields under challenging environmental conditions. These multiple benefits of neglected legumes underscore their potential in enhancing agricultural sustainability, improving food security, and strengthening the resilience of smallholder farming systems. Given their adaptability to resource-constrained environments and their role in climate resilience, increased research, policy support, and market development efforts are essential to promote their wider adoption and integration into global food systems. Despite the increasing recognition of the potential benefits of neglected legumes, a significant research gap persists regarding socioeconomic factors influencing farmers' willingness to cultivate neglected legumes and their selection of suitable planting dates.

Existing research on legume integration has predominantly focused on technical aspects, including crop productivity, soil fertility enhancement, and resistance to pests and drought. Studies have documented the agronomic performance of neglected legumes such as cowpea, pigeon pea, and Bambara groundnut, highlighting their potential contributions to sustainable agriculture. However, these studies often overlook the critical role of socioeconomic factors in shaping adoption decisions and influencing the successful cultivation of these crops into existing cropping systems. In South Africa, particularly in Bergville, KwaZulu-Natal Province, smallholder farmers face various resource constraints and agroecological challenges that significantly influence their crop choices and management practices. Therefore, this study aims to address this research gap by assessing the socioeconomic factors that influence farmers' willingness to cultivate neglected legumes and their selection of suitable planting dates in Bergville. Additionally, this research provides a more comprehensive understanding of the barriers affecting the uptake of neglected legume crops. This approach not only broadens the scope of research on neglected legume cultivation but also supports the development of targeted interventions and policies to promote the sustainable adoption of these crops in smallholder farming systems. Bridging the gap between technical recommendations and the realities of smallholder agriculture is essential to ensuring that the benefits of neglected legumes are fully realized in practice, thereby enhancing agricultural sustainability, food security, and rural livelihoods.

4.2 Materials and methods

4.2.1 Description of the Study Area

The study area, Bergville (28° 43' 49.74"S, 29° 21' 4.20"E), is located in the northern part of KwaZulu-Natal Province, South Africa (Figure 4.1). It falls within the Okhahlamba Local Municipality, which is part of the uThukela District. The region experiences a temperate climate, characterized by cool, dry winters with occasional frost and warm, wet summers. Annual precipitation ranges between 700 mm and 1200 mm, with winter minimum temperatures of 2°C to 5°C and summer maximum temperatures of 25°C to 30°C. The altitude ranges from 1,200 to 1,800 meters above sea level. Bergville was selected as the study area due to its agro-ecological significance, which is both ecologically diverse and agriculturally important. Its climatic variability, combined with semi-arid conditions, makes the region a valuable location for studying agricultural and ecological dynamics. Rainfall and temperature fluctuations in the region have a significant impact on local livelihoods and biodiversity.

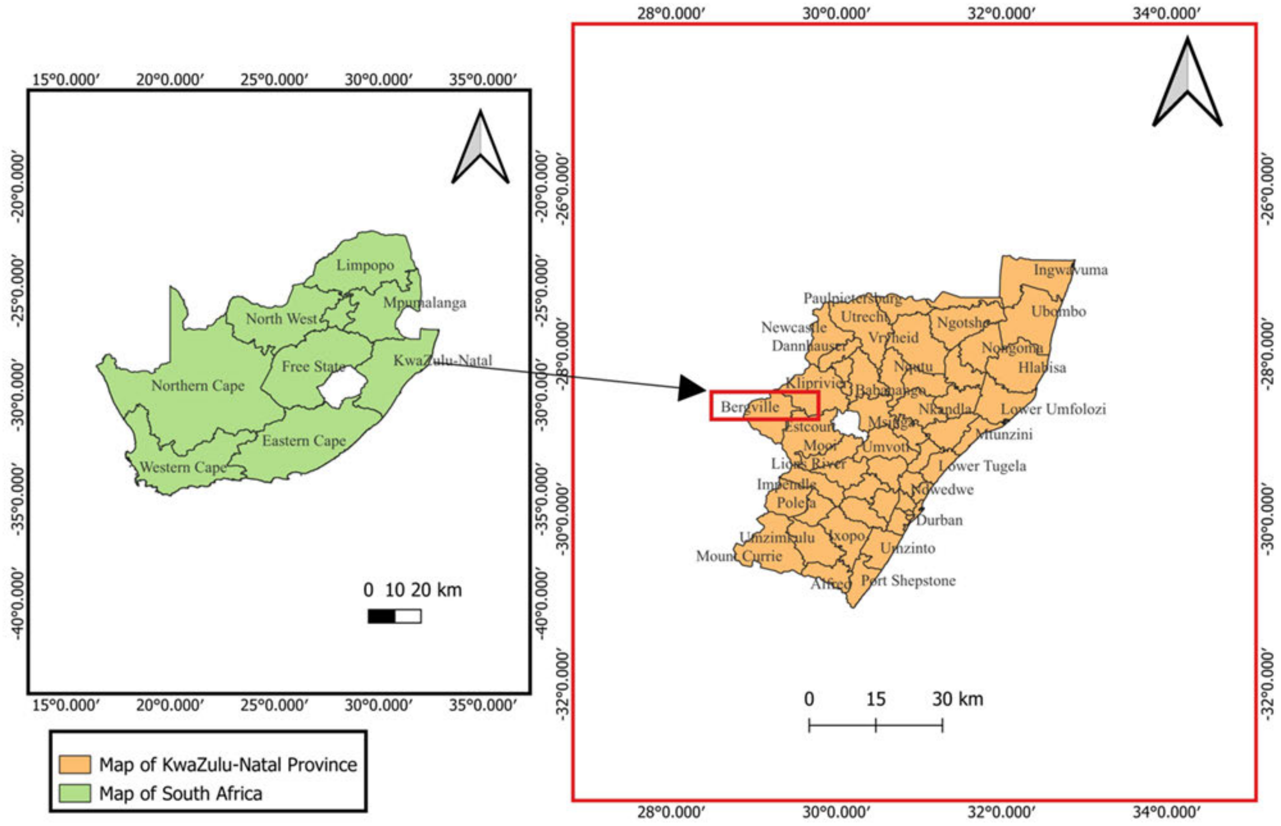

Figure 4.1: Location of Bergville in KwaZulu Natal Province, South Africa

4.2.2 Research Design

This study employed an action research design to assess farmers knowledge on neglected legumes cultivation and integration into smallholder agricultural systems. The research employed structured training sessions and implementation of field trial demonstrations. Action research, as defined by Stringer and Aragón (2020), is a collaborative and cyclical methodology that involves researchers and stakeholders, including farmers, extension officers, and community members, working together to identify problems, implement solutions, and evaluate outcomes. This participatory approach enables the generation of context-specific knowledge through continuous reflection and adaptation, making it particularly effective for addressing complex, real-world agricultural challenges in dynamic local settings.

Structured training sessions: A participatory approach was utilized to design and implement practical training sessions, ensuring relevance to local agroecological conditions and smallholder farmers' needs. The training was conducted in Bergville and included selected participants from five villages: Mlimeleni, Ezimbovini, KwanoKopela, Eqeleni, and Busingatha. These villages were selected based on agroecological variation, socio-economic diversity, and the presence of resource-constrained smallholder farmers engaged in diverse farming practices prior to engagement with the Farmers' Support Group. The program focused on enhancing farmers' knowledge of neglected legumes, emphasizing their potential benefits and the adoption of drought-tolerant cultivars. Key agronomic practices, including site selection, land preparation, planting, demonstration of proper plant spacing and intercropping strategies, integrated pest and disease management through intercropping, and crop rotation, were covered. Training encompassed harvesting, post-harvest handling, storage techniques to maintain quality and reduce post-harvest losses, neglected legumes value addition, product development, introduction to legume-based products such as flour, snacks, and animal feed, and market opportunities to promote sustainable production and economic viability.

Field trials demonstrations: Following the training sessions on the cultivation of neglected legumes, a field trial site was selected in Mlimeleni, an area characterized by a high population of smallholder farmers actively engaged in crop production. The land was prepared, and the neglected legumes including pigeon pea, Bambara groundnut and cowpea were planted alongside common bean, which is widely cultivated by farmers in the region. The legumes were planted across three planting dates to demonstrate the agronomic performance and optimal planting dates for maximizing the productivity of neglected legumes in rainfed farming systems. These legumes were also cultivated under both sole cropping and intercropping with maize to demonstrate the stability and agronomic benefits of diversified cropping systems. All participating smallholder farmers were actively involved throughout the cultivation cycle to facilitate knowledge transfer and enhance their understanding of the adaptability and agronomic potential of neglected legumes under rainfed conditions. Given that smallholder farmers in this marginalized environment often face limited access to essential agricultural resources, including capital, irrigation infrastructure, and inputs such as fertilizers and pesticides, the trials were conducted without the application of external agricultural inputs. This approach aimed to demonstrate the resilience and sustainability of neglected legumes as climate-smart crops capable of thriving under suboptimal environmental conditions. The demonstration trials highlighted the potential of neglected legumes as resilient, low-input crops capable of thriving under resource-limited, rainfed conditions. Their performance without external inputs underscores their role as climate-smart alternatives that can enhance smallholder farmers’ livelihoods through improved soil fertility, diversified cropping systems, and increased food and nutrition security. These findings emphasize the importance of promoting neglected legumes within sustainable agricultural development strategies aimed at strengthening the resilience and productivity of smallholder farming systems.

4.2.3 Research philosophical Orientation

The research was conducted based on a preliminary survey conducted to assess the status of crop diversification among smallholder farmers in the region.

Ontological assumption: Socioeconomic factors play a pivotal role in shaping the adoption of crop diversification, particularly the cultivation of neglected legumes and their integration into smallholder farming systems. Constraints such as limited land availability, water scarcity, restricted market access, and varying levels of education significantly influence farmers' ability to diversify their crop choices. Demographic and experiential factors, including marital status, household size, farming experience, and perceived benefits of crop diversification, further impact diversification decisions. Limited awareness or technical knowledge also serves as a barrier to diversification. Moreover, older farmers are less inclined to adopt diversified cropping systems due to factors such as risk aversion, adherence to traditional farming practices, physical limitations, and a lower propensity to embrace innovative agricultural techniques.

Epistemological assumptions: Farmers who perceive the potential benefits of legume crop diversification are more likely to adopt diverse cropping practices. Consequently, the cultivation of neglected legumes and their integration into smallholder farming systems can be achieved through targeted interventions designed to enhance farmers' knowledge of diversification strategies. The implementation of farmer training workshops and the promotion of participatory learning approaches can serve as effective mechanisms for knowledge transfer, ultimately fostering the wider adoption of legume crop diversification.

Axiological assumptions: Knowledge transfer and demonstration trials are expected to influence smallholder farmers' willingness to cultivate neglected legumes into cropping systems, providing a true reflection of the transformative experiences anticipated from this research.

Based on the synthesis of these assumptions, this study adopts a transformative paradigm. According to Dhanaraj et al. (2024), research grounded in the transformative paradigm aims to empower individuals to initiate change and take action to transform society. Education has been shown to effectively alter farmers' beliefs and behaviours, leading to long-lasting impacts. This research seeks to shift farmers' perspectives on neglected legumes, promoting the adoption of climate-resilient cropping strategies, with the goal of enhancing food security, income stability, and rural livelihoods.

4.2.4 Research approach

Following the structured training sessions on neglected legumes and trial demonstrations, a mixed-methods approach was employed to ensure a comprehensive analysis of farmers' cultivation and the adoption of neglected legumes into cropping systems. This approach incorporated surveys, key informant interviews, and focus group discussions.

4.2.5 Sampling procedure and sample size

The study adopted a quantitative research approach and employed a descriptive survey research design. According to Bless et al. (2006), descriptive and quantitative research methods are critical for examining beliefs, attitudes, and emerging patterns within a given population. The study's target population included all farmers who were affiliates of the Farmers' Support Group (FSG) at the time of the research, with eligibility limited to smallholder farmers specializing in crop production. The FSG's criteria were to register all resource-constrained smallholder farmers in the region with diverse farming practices and socio-economic backgrounds, ensuring inclusivity and support for a broad range of agricultural activities. A two-stage sampling procedure was employed to select respondents for the study. In the first stage, purposive sampling was employed to select smallholder crop farmers from the Farmers' Support Group. In the second stage, a simple random sampling method was used to select participants from this group, ensuring adequate representation and preserving the diversity among the smallholder crop farmers. The target population comprised 240 smallholder farmers. The sample size was determined according to Yamane (1973), ensuring an unbiased and statistically representative selection of participants. This method accounts for population size and desired precision to enhance the reliability of findings. Applying a 95% confidence level and a 5% margin of error, the computed sample size comprised 150 randomly selected smallholder farmers from five villages (Mlimeleni, Ezimbovini, KwanoKopela, Eqeleni, and Busingatha) in Bergville.

The following calculation demonstrates the method used to determine the appropriate sample size.

$$\mathrm{n} = \frac{\mathrm{N}}{1 + \mathrm{Ne}^2} = \mathrm{n} = \frac{240}{1 + 240(0.05)^2} = 150$$

where n = sample size (150); N = population size of smallholder farmers (240); e = desired margin of error (0.05).

4.2.6 Data Collection and Analysis

4.2.6.1 Baseline survey

A structured questionnaire was developed as the primary survey instrument to elicit data for the study. Prior to the data collection process, four (4) enumerators were trained to assist with data collection. In-formed consent was obtained from all participating farmers, and participation was voluntary. Data were collected through face-to-face interviews using structured questionnaires, adhering to all protocols and ethical principles outlined in the Declaration of Helsinki. The questionnaire was face and content validated by field experts in the field of agronomy to ensure relevance and applicability prior to data collection. This evaluation assessed its structure and relevance and examined whether the included variables were reasonable and clear. In addition, a reliability assessment was conducted through a pre-test to determine the instrument's stability and consistency in measuring the intended variables. The pre-test method was applied to ten (10) smallholder farmers from a village not included in the study. A reliability coefficient of $r = 0.85$ was obtained, which, according to established standards in the literature, indicates that the questionnaire was reliable (Mulaudzi et al., 2024). The survey instrument comprised sections aligned with specific study objectives, assessing socioeconomic factors influencing farmers' willingness to cultivate neglected legumes and their selection of suitable planting dates. To enhance clarity and cultural appropriateness, interviews were conducted in isiZulu, the native language of the respondents, ensuring effective communication and improving the reliability of responses. A total of 150 questionnaires were successfully administered across the five villages, with all participants being local smallholder farmers actively engaged in crop production.

4.2.6.2 Key informant interviews

In each of the five villages, five key informants were selected based on their roles and expertise within the community. These informants included agricultural extension officers, schoolteachers, community members, healthcare workers, and smallholder farmers. The local chief was also interviewed due to their leadership position and in-depth knowledge of the community's social, cultural, and agricultural dynamics. Community leaders, many of whom were smallholder farmers, were included to provide additional perspectives on the integration of neglected legumes. The inclusion of this diverse group of informants ensured a comprehensive understanding of local farming practices, awareness of neglected legumes, and the challenges and opportunities associated with their adoption. The insights gained from these interviews were crucial in informing the subsequent stages of the research, particularly regarding local agricultural practices, challenges, and opportunities.

4.2.6.3 Focus Group Discussions

To gain in-depth insights into the perspectives of smallholder farmers, focus group discussions (FGDs) were utilized as a key qualitative data collection method. Each FGD consisted of 10 participants, ensuring balanced representation in terms of gender and age. Participants ranged in age from ≤ 25 to 66 years. The participants were randomly selected from the villages to minimize selection bias and ensure diverse viewpoints reflective of the broader farming community. The discussions were guided by a set of open-ended questions, designed to elicit detailed and nuanced responses from participants. This approach allowed smallholder farmers to share their experiences, opinions, and challenges in an unrestricted and interactive manner. Efforts were made to create a comfortable and inclusive environment that encouraged open dialogue. While ensuring equal participation among participants presented challenges, specific measures were implemented to address this. Enumerators were trained to actively engage quieter participants, redirect dominating conversations, and ensure that each individual had the opportunity to respond to every question posed. This strategy aimed to reduce imbalances in participation and enhance the comprehensiveness of the data collected.

The survey data were imported from an Excel file into IBM SPSS (Statistical Package for the Social Sciences) software, version 30, for analysis. A systematic review of variable names was conducted to ensure clarity and consistency in coding. During the data cleaning process, missing values were identified and addressed using multiple imputation, which accounts for uncertainty by creating several imputed datasets and combining the results for robust estimation. Outliers were detected through box plots and z-scores and were excluded to maintain the dataset's integrity. Categorical variables were recoded for uniformity, with numerical codes assigned where applicable to facilitate statistical analysis. Following data preparation, descriptive statistical analyses were performed using SPSS, providing frequency distributions, percentages, means, and standard deviations for both continuous and categorical variables in alignment with the study’s research objectives. Results were presented using tables, pie charts, and bar graphs to enhance clarity and interpretability. Additionally, a multivariate probit regression model was employed to examine the socio-economic factors influencing smallholder farmers' willingness to cultivate neglected legumes and their selection of various suitable planting dates.

4.2.7 Model specification

4.2.7.1 Multivariate probit model (MVP)

The study also utilized a multivariate probit model approach to examine the socio-economic determinants of farmers' willingness to cultivate neglected legumes and their selection of various suitable planting dates. In contrast to other dichotomous models, the MVP model effectively accounts for unobservable factors that influence smallholder farmers cultivation of neglected legumes and planting dates by permitting correlation across error terms of latent equations. The identified correlations allow for error terms that indicate positive correlation (complementarity) and negative correlation (substitutability) on legumes cultivation and planting dates. In this study, the MVP model consists of four binary choice equations for neglected legumes (pigeon pea, cowpea, Bambara groundnut and common bean) and three binary choice equations for suitable planting dates (November, December and January).

Hence, the study model is specified as:

$$P* im = βim + xim + εim \ (m = 1, 2, 3…) \qquad (1)$$

$$Pim \ \{1 \text{ if } P* im > 0 \text{ and } 0 \text{ otherwise}\}$$

The above equation is formulated under the assumption that a rational i-th farm household possesses a latent variable P∗im which captures unobserved factors influencing the m-th neglected legumes selection and planting dates (m= 4 neglected legumes selection in the first model and planting dates in the second model). Xim consists of exogenous variables that determine neglected legumes selection as well as planting dates, including smallholder farmers' socioeconomic attributes as detailed in Figure 2 and Table 1. The coefficients βm quantify the effects of these explanatory variables on neglected legumes selection and planting dates. The error terms εim follow a multivariate normal distribution, each with a mean of zero and a variance–covariance matrix characterized by values of 1 along the diagonal and nonzero correlations among off-diagonal elements.

4.2.8 Ethical Consideration

Ethical clearance for this study was obtained from the University of KwaZulu-Natal Ethics Committee, facilitated by the School of Agricultural, Earth, and Environmental Sciences, under reference number HSSREC/00008179/2025 (ethical clearance approval included in Appendix A). During the administration of the questionnaires, the researcher sought informed consent from the participants, ensuring confidentiality throughout the process. The questionnaires were distributed at times and locations that were convenient for the participants. Before completing the questionnaires, participants were fully informed about the scope of the study, and their anonymity was preserved by not disclosing any personal identities. The study was conducted with a strong emphasis on participant welfare, ensuring that no harm was inflicted during the process. Furthermore, all participants were acknowledged and thanked for their valuable time and contribution to the completion of the questionnaires.

4.3 Results

4.3.1 Socioeconomic Characteristics of Smallholder Farmers in the Study Area

The data illustrated in Figure 4.2 provide a comprehensive overview of the socioeconomic profile of smallholder farmers within the study area. A majority of the respondents (53%) were aged between 26 and 50 years, followed by 41% who were 51 years and above, while only 6% were aged 25 years or younger (Figure 4.2A). The results also showed that 72% of smallholder farmers were female, while males accounted for 28% (Figure 4.2B). Regarding educational attainment, 47% of respondents had completed secondary education, 25% had primary education, and 22% had no formal education. In contrast, only 6% had attained tertiary education (Figure 4.2C). Marital status indicated that a significant proportion (53%) of farmers were unmarried, while 35% were married and 12% were widowed (Figure 4.2D). As shown in Table 4.1, slightly more than half (51.4%) of the farmers lived in households with six to ten members, while 31.3% had one to five members. Only 17.3% lived in households with eleven or more members. Furthermore, the findings revealed that the primary source of income for most farmers (70.7%) was welfare grants. Other sources of income included irrigated crop farming (28.7%), rainfed crop farming (13.3%), livestock sales (16.7%), remittances (20%), and temporary employment (16%). Additionally, 10% of farmers relied on other income-generating activities, such as sewing and handicrafts.

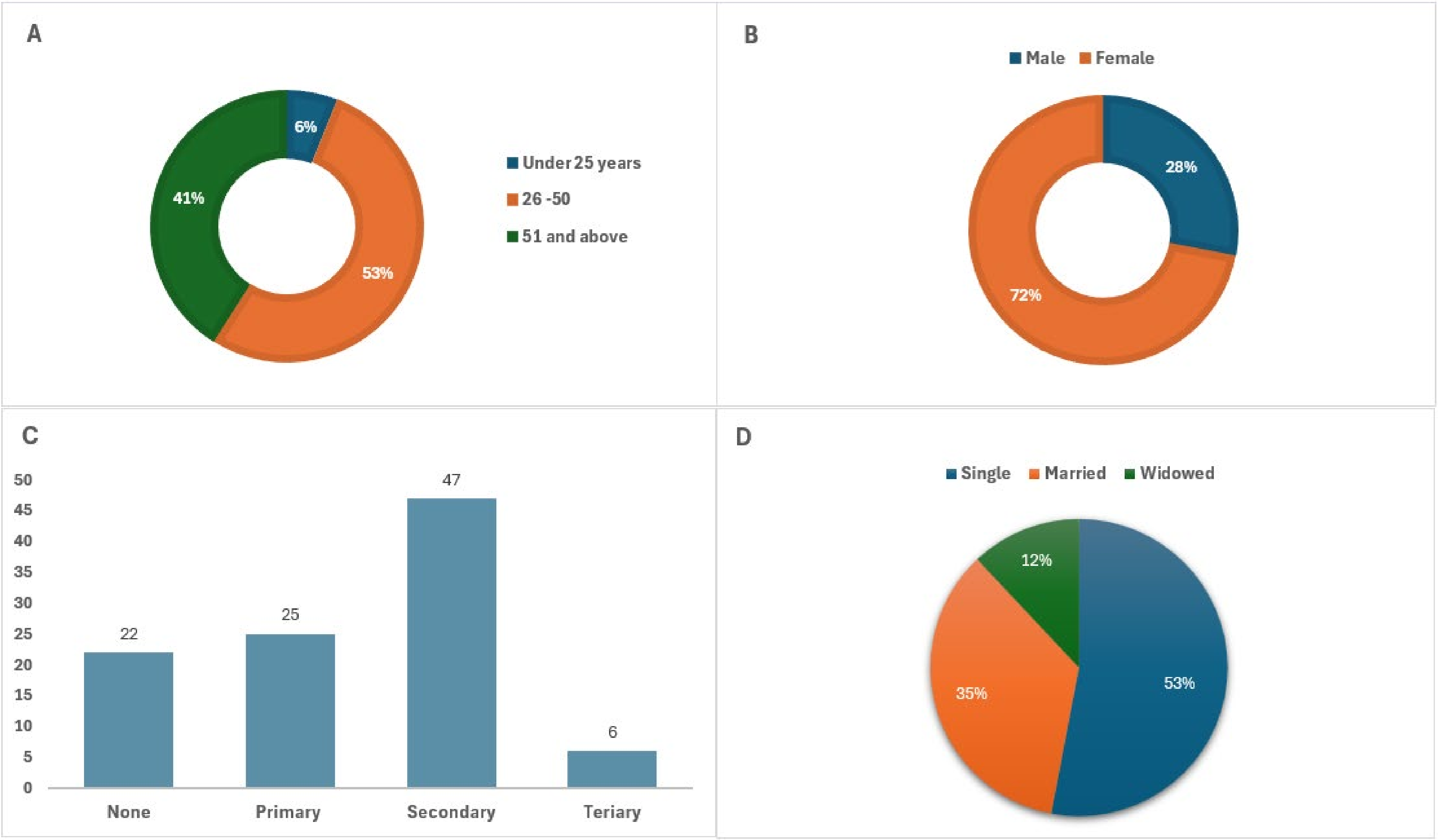

Figure 4.2: Socioeconomic characteristics of smallholder farmers. (A) Age of respondents. (B) Gender of respondents. (C) Respondents' education level. (D) Marital status of respondents.

Table 4.1 further indicated that 66.7% of farmers primarily sourced their food from supermarkets, while 32.7% produced their own food, and only 0.7% depended on food schemes or aid programs. In terms of farming experience, the majority (85.3%) had between one and ten years of experience, 10.7% had between eleven and twenty years, while 2% had between twenty-one and thirty years, and another 2% had over thirty years of experience. Land ownership showed that 92.7% of respondents owned less than two hectares of land, 6.7% owned between three and five hectares, and only 0.7% owned more than six hectares. Moreover, the findings indicated that a substantial majority of farmers (79%) had not received any prior training on neglected legumes, with only 20.7% having participated in such training before the study commenced. In terms of water sources for agricultural activities, 65.3% of farmers utilized a combination of rainfall and irrigation, while 25% relied exclusively on rainfall, and 9.3% depended solely on irrigation. With respect to seed sourcing, most farmers (71.3%) acquired seeds from supermarkets, whereas 21.3% preserved seeds from previous harvests for future use. A small proportion (7.3%) sourced seeds from institutions such as the Department of Agriculture and the Farmers Support Group. Lastly, market access remained a significant challenge, with 80.7% of farmers reporting no access to markets, while only 19.3% had market access.

Table 4.1: Distribution of the Socio-economic characteristics of smallholder farmers Contd.

Socio-Economic Variables	Frequency (%)
Household Size	
1-5 people	47 (31.3)
6-10 people	77 (51.4)
11 and above	26 (17.3)
***Source of income**	
Temporal employment	24 (16.0)
Welfare grant	106 (70.7)
Remittances	30 (20.0)
Crop sales - irrigated	43 (28.7)
Crop sales - rainfed	20 (13.3)
Livestock sales	25 (16.7)
Other	15 (10.0)
Source of food	
Own production	49 (32.7)
Purchased	100 (66.7)
Food aid	01(0.7)
Years of farming experience	
1-10yrs	128 (85.3)

11-20yrs	16(10.7)
21-30yrs	3 (2.0)
31 and above	3 (2.0)
Farm size (hectares)	
≤ 2	139 (92.7)
3-5 ha	10 (6.7)
6 and above	1 (0.7)
Training on legumes	
Yes	31 (20.7)
No	119 (79.)
Sources of water for irrigation	
Irrigation	14 (9,3)
Rainfall	38 (25.3)
Both	98 (65.3)
Sources of seeds	
Own production	32 (21.3)
Supermarkets	107 (71.3)
Other	11 (7.3)
Market access	
Yes	29 (19.3)
No	121 (80.7)

* Multiple choice response

4.3.2 Overview of Cropping Practices in the Surveyed Region

Figure 4.3 provides a detailed analysis of the agricultural practices employed by smallholder farmers within the study area. A significant proportion (87%) cultivate vegetables, followed by 55% who grow cereals, while only 43% cultivate legumes (Figure 4.3A). Regarding cropping systems, 48% of respondents practice intercropping, 35% engage in monoculture, and 15% implement crop rotation. In contrast, only 1.3% practice relay cropping (Figure 4.3B). The frequency of legume cultivation varied among farmers. The majority (49%) reported never cultivating legumes, while 20% rarely grew them, and 12% cultivated legumes sometimes or often. Only 7% grew legumes every season (Figure 3C). Additionally, the findings revealed that 52% of farmers cultivated legumes in January, 28% in February, and 15% in November. A small proportion (5%) planted legumes in December (Figure 4.3D).

To verify the types of crops cultivated in the region, both key informants and focus groups reported the following:

"Crop production in the study area is primarily focused on vegetable cultivation, followed by cereals, while a smaller proportion of farmers engage in legume farming. The predominant legumes grown include sugar bean (*Phaseolus vulgaris*), kidney bean *(Phaseolus vulgaris*), and cowpea (*Vigna unguiculata*). Vegetable cultivation encompasses a wide range of crops, including spinach (*Spinacia oleracea*), beetroot (*Beta vulgaris*), onion (*Allium cepa*), carrot (*Daucus carota*), green pepper (*Capsicum annuum*), sweet potato (*Ipomoea batatas*), potato (*Solanum tuberosum*), chili pepper (*Capsicum spp.*), eggplant (*Solanum melongena*), and cabbage (Brassica oleracea). The primary cereals cultivated in the region are maize (*Zea mays*) and wheat (*Triticum aestivum*)."

Regarding planting dates, focus group discussions stated:

"Majority of farmers cultivate legumes in January, as this period experiences reduced rainfall. In contrast, excessive rainfall in December often leads to pod abortion and seed rot, making it less favourable for legume cultivation."

The focus group discussions further indicated:

"Although nearly half of the farmers practice intercropping, primarily integrating maize (*Zea mays*) with pumpkins (*Cucurbita spp.*) or sugar beans (*Phaseolus vulgaris*), a significant proportion continue to rely on monoculture. The persistence of monoculture is attributed to several factors, including limited land availability, reliance on rainfall as the primary water source for irrigation, financial constraints that hinder seed acquisition, and a shortage of labour. The challenge is exacerbated by minimal youth participation in agriculture, as younger individuals often perceive farming as an occupation primarily suited for older generations."

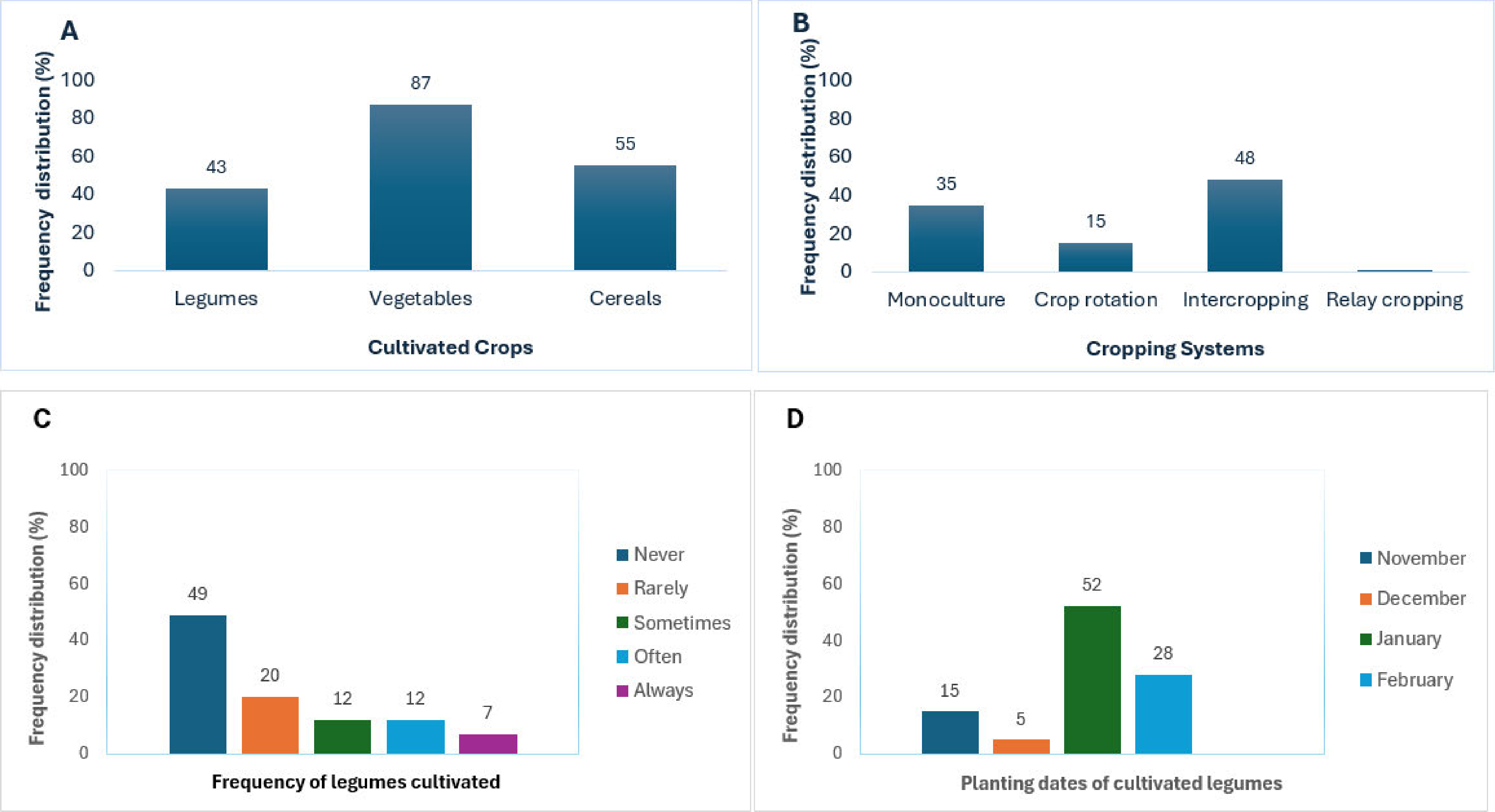

Figure 4.3: Overview of cropping practices in the surveyed region. (A) Crops cultivated by smallholder farmers. (B) Dominant cropping systems. (C) Frequency of legumes cultivation. (D) Planting dates of cultivated legumes.

4.3.3 Training Participation and Knowledge of Legumes in the Surveyed Region

A majority of smallholder farmers (79.3%) had never participated in legume training, while just 20.7% had attended such training (Table 4.2). An assessment of farmers' knowledge about legumes in the region revealed that a large proportion (85.3%) were unfamiliar with legume cultivars, with only 14.7% having any knowledge. Similarly, knowledge about legume production was scarce, as only 7.3% of farmers had relevant expertise, while 92.7% lacked understanding of legume cultivation. When it came to legume adaptability, only 5.3% of farmers were knowledgeable, leaving 94.7% unaware of this aspect. Additionally, understanding of the legume market was limited, with 94.7% of farmers having no knowledge of market trends and only 5.3% possessing any insights into market dynamics.

Table 4.2: Training participation and knowledge of legumes in the surveyed region

Tested knowledge of legumes in the region	**Frequency (%)** **Yes**	**Frequency (%)** **No**
a. Have you been trained on legumes before?	31 (20.7)	119 (79.3)
b. Do you have knowledge of legume cultivars?	22 (14.7)	128 (85.3)
c. Do you have knowledge of legume production?	11 (7.3)	139 (92.7)
d. Do you have knowledge of legume adaptability?	8 (5.3)	142 (94.7)
e. Do you have knowledge of legume market?	8 (5.3)	142 (94.7)

To corroborate the challenges related to the lack of training and awareness regarding neglected legumes, as highlighted by the quantitative study, both key informants and focus group discussions emphasized the following:

“Respondents identified a gap in knowledge and resources, which hinders the adoption and cultivation of underutilized crops. The lack of training programs and extension services specifically targeting neglected legumes was noted as a significant barrier, limiting farmers' ability to diversify their crop production. Additionally, the absence of awareness campaigns and technical support further exacerbates the issue, as many farmers are unfamiliar with the potential benefits and cultivation practices associated with neglected legumes. Consequently, these challenges contribute to the low uptake and limited cultivation of neglected legumes in the region.”

One of the key informants stated:

"The low intake of legumes in local diets is primarily attributed to their high cost in supermarkets, which limits their accessibility to many consumers. Additionally, farmers in the region tend to produce legumes in small quantities, which further exacerbates the issue by preventing the establishment of reliable local markets. The limited scale of production restricts the availability of legumes in both retail and wholesale markets, making them less competitive compared to other staple crops. Consequently, the low market supply, coupled with high prices, creates a significant barrier to increasing legume consumption. This cycle is reinforced by the lack of market infrastructure and proper supply chains, which could otherwise facilitate the distribution of legumes at more affordable prices. Therefore, addressing both production challenges and market access is critical to improving legume consumption in the region."

4.3.4 Pre-Training Knowledge Levels of Smallholder Farmers on the Benefits of Neglected Legumes

The results in Table 4.3 revealed that the majority (73.3%) of farmers had extensive knowledge of neglected legumes' richness in proteins, carbohydrates, fibre, minerals, vitamins, and micronutrients, while 26.7% had limited knowledge. In contrast, 76% of respondents were unaware that neglected legumes can help lower the risk of heart disease, diabetes, cancer, and obesity, while only 24% recognized this potential benefit. Regarding legumes' ability to improve soil fertility and reduce the need for nitrogen fertilizers through biological nitrogen fixation, only 35.3% of farmers had knowledge, whereas 64.7% were unaware of it. Additionally, 73.3% of farmers did not know that legumes can help break the cycle of pests and diseases, while 26.7% were aware of this benefit. More than three-quarters (78%) of respondents had limited or no knowledge of legumes' ability to conserve soil water, while only 22% were aware of this function. Only a small minority (5.3%) of respondents understood legumes' role in promoting ecosystem stability in marginal environments, whereas a significant majority (94.7%) lacked knowledge in this area.

Table 4.3: Pre-training knowledge levels of smallholder farmers on the benefits of neglected legumes

Tested knowledge on neglected legumes benefits	**Frequency (%) Yes**	**Frequency (%) No**
a. Neglected legumes are rich in proteins, carbohydrates, fibre, minerals, vitamins, and micronutrients.	110 (73.3)	40 (26.7)
b. Neglected legumes lower the risk of heart disease, diabetes, cancer, and obesity.	36 (24.0)	114 (76.0)
c. Neglected legumes improve soil fertility and reduce the need for nitrogen fertilizers through biological nitrogen fixation.	53 (35.3)	97 (64.7)
d. Neglected legumes break the cycle of pests and diseases.	40 (26.7)	110 (73.3)
e. Neglected legumes conserve soil water.	33 (22.0)	117 (78.0)
f. Neglected legumes promote ecosystem stability in marginal environments.	8 (5,3)	142 (94.7)

4.3.4.1 Post-Training Knowledge Levels of Smallholder Farmers on the Benefits of Neglected Legumes

The results in Figure 4.4 illustrate the knowledge levels of smallholder farmers regarding the benefits of neglected legumes following the training provided by the study. A significant proportion (81%) demonstrated strong knowledge, defined as the ability to identify at least four legume cultivars and five functions of legumes. Additionally, 15% exhibited weak knowledge, characterized by the ability to name at least two legume cultivars and two functions. In contrast, only a small minority (4%) showed no knowledge, as they were unable to identify any legume cultivars or functions of neglected legumes.

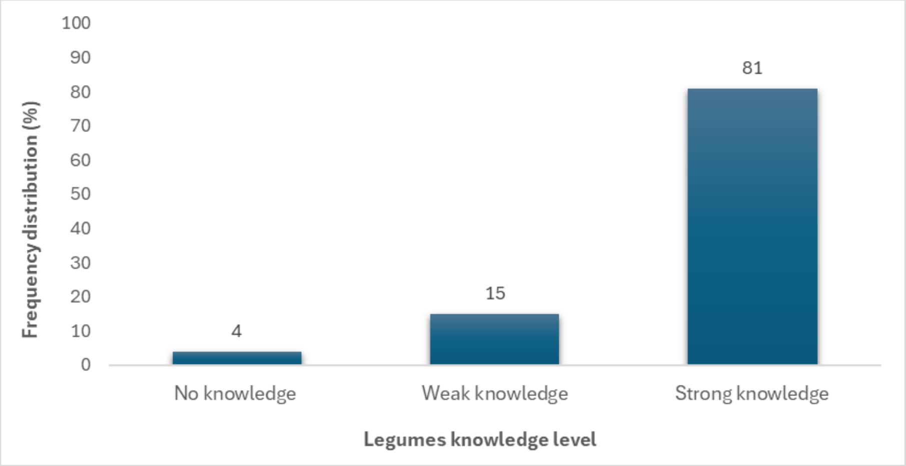

Figure 4.4: Post-training knowledge levels of smallholder farmers on the benefits of neglected legumes.

4.3.5 Farmers' Participation in Neglected Legume Training, Adoption Willingness, and Post-Training Cropping System Integration

The results presented in Figure 4.5 indicated that a significant proportion (92%) of respondents participated in the training on neglected legumes conducted in this study, while 8% did not participate (Figure 4.5A). Following the training and trial demonstrations, the majority of farmers (96%) expressed a willingness to integrate legumes into their cropping systems, whereas 4% remained reluctant to adopt neglected legumes (Figure 4.5B). Additionally, farmers who previously practised monoculture have shown interest in adopting intercropping. Consequently, 89% transitioned to an intercropping system, while a minority (11%) preferred to continue with monoculture (Figure 4.5C).

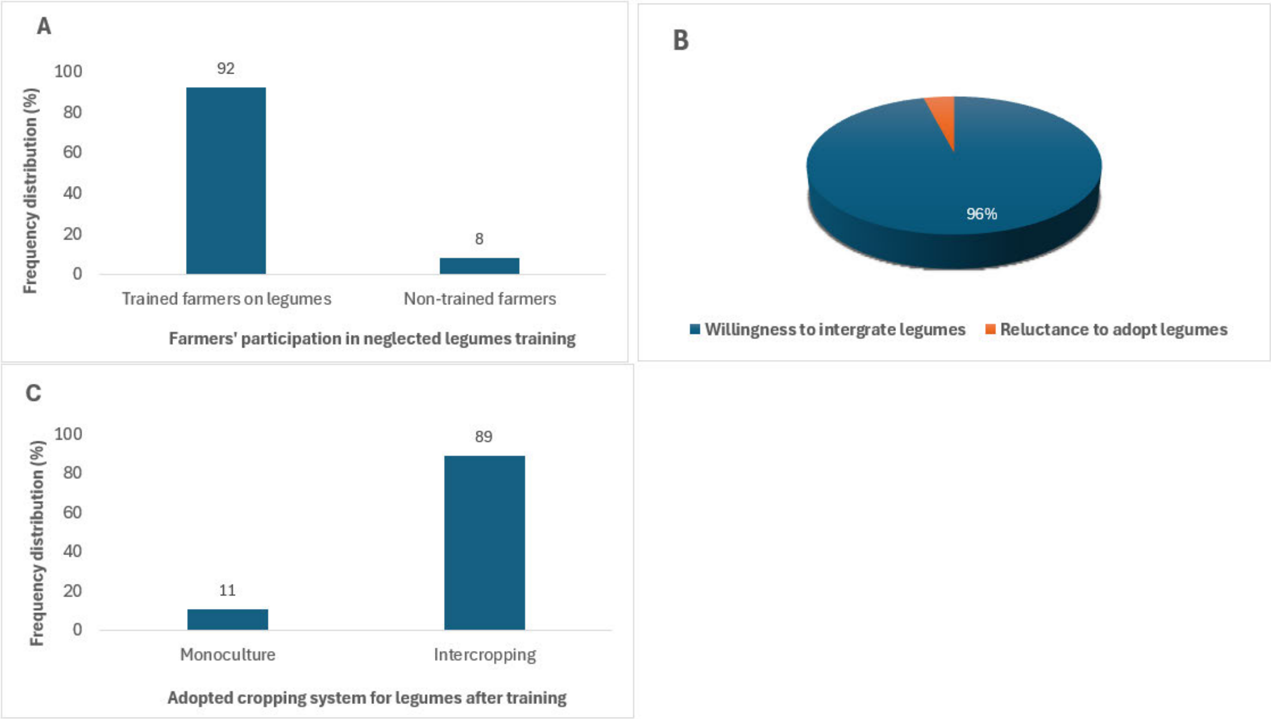

Figure 4.5: (A) Farmers' participation in neglected legume training. (B) Willingness to integrate legumes into the cropping system. (C) Adopted cropping system for legumes post-training.

4.3.6 Socio-Economic Factors Influencing Farmers' Willingness to Cultivate Neglected Legumes

The results in Table 4.4 present the socioeconomic factors influencing smallholder farmers' willingness to cultivate neglected legumes in Bergville, as analysed using a multivariate probit regression model. The Wald test (chi2 (44) = 40.27, Prob > chi2 = (0.632)) was insignificant at $P > 0.05$. The insignificant ($P > 0.05$) socioeconomic factors included age, gender, household size, farming experience, and sources of seeds. However, training on legumes ($P < 0.1$) had a significant positive influence on pigeon pea cultivation. Additionally, both marital status ($P < 0.1$) and legume training ($P < 0.05$) significantly influenced farmers' willingness to cultivate cowpea. Furthermore, farm size ($P < 0.1$), market access ($P < 0.1$), and sources of water for irrigation ($P < 0.05$) were positively associated with farmers' willingness to cultivate common bean. Among the examined factors, only sources of water for irrigation ($P < 0.1$), were significantly related to the selection of Bambara groundnut.

4.3.7 Socio-Economic Determinants Influencing Farmers' Selection of Optimal Planting Dates

The results in Table 4.5 present the socioeconomic determinants influencing smallholder farmers' selection of optimal planting dates, using a multivariate probit regression model. The Wald test (chi2 (33) = 31.65, Prob > chi2 = (0. 534)) was not significant ($P > 0.05$), indicating that the overall model fit was not statistically significant. Among the socioeconomic determinants, age, gender, marital status, farming experience, and seed sources were not significant ($P> 0.05$). However, farm size ($P < 0.1$) and legume training ($P < 0.1$) significantly influenced the selection of a November planting date. Similarly, household size ($P < 0.05$) and legume training ($P < 0.1$) had a significant effect on selecting a December planting date. Additionally, water sources for irrigation ($P < 0.1$) and legume training ($P < 0.1$) were positively associated with the selection of January planting date.

Table 4.4: Socio-economic factors influencing farmers' willingness to cultivate neglected legumes

*, **, and *** signify statistical significance at p< 0.1, p<0.05 and p<0.01 levels, respectively.

Characteristics	Pigeon pea		Cowpea		Bambara groundnut		Common bean	
	Coeff.	**Std.Err**	**Coeff.**	**Std.Err**	**Coeff.**	**Std.Err**	**Coeff.**	**Std.Err**
Age	0.346	0.086	0.064	0.085	0.034	0.087	0.082	0.093
Gender	0.109	0.247	-0.183	0.239	0.033	0.245	0.084	0.263
Marital status	-0.166	0.137	-0.249	0.140*	0.458	0.143	-0.006	0.149
Household size	0.335	0.030	-0.009	0.029	0.003	0.230	0.010	0.033
Farming experience	0.072	0.094	-0.010	0.093	0.070	0.099	-0.047	0.093
Farm size	-0.160	0.280	-0.343	0.311	0.323	0.428	-0.507*	0.302
Training on legumes	0.479*	0.289	-0.589	0.276**	-0.159	0.275	-0.124	0.295
Source of seeds	0.186	0.218	-0.244	0.217	-0.242	0.233	-0.073	0.228
Market access	-0.352	0.281	-0.151	0.282	0.226	0.301	-0.465*	0.291
Sources of water for irrigation	-0.174	0.333	-0.120	0.166	0.192	0.270*	0.295**	0.173
Constant	-0.060	0.764	1.754	0.788	-0.281	0.864	0.282	0.847
N	150							
Wald chi2 (44)	40.27							
Log- likelihood	-353.155							
Prob > chi2	0.632							

Table 4.5: Socio-economic determinants influencing farmers' selection of optimal planting dates

Characteristics	**November**		**December**		**January**	
	Coeff.	Std.Err	Coeff.	Std.Err	Coeff.	Std.Err
Age	-0.124	0.089	0.132	0.086	0.028	0.089
Gender	0.188	0.251	-0.109	0.238	0.172	0.269
Marital status	-0.162	0.135	-0.060	0.133	-0.033	0.140
Household size	0.011	0.031	-0.019**	0.029	-0.031	0.030
Farming experience	0.088	0.095	0.078	0.088	-0.001	0.095
Farm size	-0563*	0.311	-0.599	0.420	-0.034	0.293
Training on legumes	-388*	0.275	0.403*	0.268	0.379	0.326*
Source of seeds	-0.326	0.230	0.134	0.217	-0.005	0.233
Market access	0.142	0.293	0.129	0.279	-0.265	0.294
Sources of water for irrigation	0.145	0.174	-0.229	0.170	0.293**	0.173**
Constant	1.661	0.836	0.620	0.823	-0.005	0.841
N	150					
Wald chi2 (33)	31.65					
Log- likelihood	-261.935					
Prob > chi2	0.534					

4.4 Discussion

4.4.1 Socioeconomic Characteristics of Smallholder Farmers in the Study Area

The study findings indicated that only 6% of smallholder farmers were aged 25 years or younger, while 41% were aged 51 years or older. These results suggested limited engagement of youth in agriculture, potentially due to the perception that farming is predominantly an occupation for older generations (Geza et al., 2021). These findings align with those of Sithole and Olorunfemi (2024), who reported that young people are not actively engaging in agriculture-related activities. According to Chipfupa and Tagwi (2021), the declining participation of youth in agriculture has become a significant concern, with empirical evidence suggesting that young individuals perceive the sector as a low-productivity and last-resort livelihood. This can be attributed to various socioeconomic factors, including limited access to agricultural resources, concerns about financial viability, and the perceived attractiveness of urban employment opportunities. However, this demographic imbalance may hinder the integration of neglected legumes into cropping systems, as younger farmers are generally more inclined to adopt innovative agricultural practices and technologies. While the involvement of older farmers contributes to short-term agricultural productivity, concerns persist regarding the long-term sustainability of the sector if younger generations continue to disengage. As highlighted by Osabohien et al. (2021) and Terefe (2025), youth participation in agriculture is essential for ensuring sustainable socioeconomic development.

The study further revealed that women constitute a substantial proportion (72%) of smallholder cropping systems, underscoring their crucial role in agricultural production. This finding is consistent with previous research, which has demonstrated that women contribute significantly to crop production, surpassing men (Glazebrook et al., 2020; Mukaila et al., 2021). This reinforces the critical role of women in ensuring food security in the Global South, despite persistent structural inequalities that hinder their productivity and economic empowerment. Furthermore, the results revealed that a minority (6%) of farmers had attained tertiary education, while the majority lacked formal education. This disparity presents a significant concern, as higher education levels are generally associated with improved comprehension of agronomic practices and a greater propensity for adopting innovative cropping strategies. The findings suggest that farmers without formal education may encounter challenges in accessing and interpreting scientific research, agricultural extension services, and market trends related to neglected legumes. Consequently, these farmers tend to rely on traditional farming methods and may demonstrate hesitancy in adopting novel crops due to apprehensions about failure, unfamiliarity, or entrenched misconceptions. These findings align with those of Ge et al.

(2023), who identified limited education and restricted access to agricultural information as key barriers to crop diversification, particularly among female farmers. Bridging these educational gaps through targeted extension services, knowledge dissemination, and capacity-building initiatives could enhance the adoption of neglected legumes and foster more resilient and sustainable agricultural systems.

The high proportion of unmarried farmers (53%) presented significant implications for smallholder farmers' capacity to cultivate or adopt neglected legumes. Marital status plays a crucial role in determining access to labour, decision-making autonomy, and financial stability, all of which are essential for agricultural innovation and diversification. As noted by Ge et al. (2023), restricted decision-making power among female farmers often leads to reluctance in adopting new crops. This suggests that unmarried farmers, particularly women, may encounter additional barriers to integrating neglected legumes into their farming systems due to structural constraints in resource access and limited autonomy in agricultural decision-making. Moreover, women often face significant barriers to securing land ownership. The findings confirmed that 92.7% of respondents owned less than two hectares of land, highlighting the structural challenges women encounter in acquiring agricultural resources. Limited land ownership among farmers, particularly women, significantly affects crop diversity, as reported by Schling et al. (2024). Addressing these land-related constraints through policies that promote equitable land access, tenure security, and targeted support for neglected legumes cultivation could facilitate the integration of legumes into smallholder cropping systems, ultimately enhancing soil health and improving farmer livelihoods.

Most households comprised six to ten members, suggesting that most farmers have relatively large families. This finding indicates that family size may influence the adoption of neglected legumes in the region, as it determines the availability of labour, as noted by Foguesatto et al. (2020). Furthermore, the findings revealed that the primary source of income for most farmers (70.7%) was social welfare grants. These results align with those of Mkuhlani et al. (2020), who reported that most resource-constrained farmers, including social welfare-dependent and struggling subsistence farmers, are unemployed. Consequently, they are unable to invest in farming and face food insecurity. Due to financial constraints, they rely on limited inputs, such as minimal fertilizer application, leading to reduced productivity (Nyambo et al., 2022; Touch et al., 2024). This was confirmed by the study findings, which indicated that 66.7% of farmers primarily sourced their food from supermarkets, while others depended on food schemes or aid programs due to low yields, soil degradation, and other factors. However, integrating legumes into their farming systems could enhance soil fertility, reduce dependency on external inputs, and improve food security by providing a cost-effective and nutrient-rich crop option.

The findings also revealed that market access remains a significant challenge, with 80.7% of farmers lacking access to formal markets. This limitation may be attributed to farmers' reliance on informal markets for selling their surpluses due to inadequate linkages with formal market structures. Similar findings were reported by Hlatshwayo et al. (2021). These results underscore the need to reassess policies and institutional frameworks that support smallholder participation in formal markets. Strengthening market access could promote neglected legume cultivation in the region by enhancing profitability and incentivizing adoption. In addition, despite 85.3% of farmers demonstrating extensive farming experience, the results revealed that 79% had never received training on neglected legumes. This indicates that the low adoption of underutilized crops, such as neglected legumes, may be primarily attributed to insufficient technical knowledge, limited extension support, and inadequate awareness of their agronomic and nutritional benefits. Strengthening farmer education through targeted training and extension services is essential to promote the adoption and integration of these crops into farming systems, thereby enhancing food security and contributing to long-term agricultural sustainability. The study results also revealed that 9.3% of farmers relied exclusively on irrigation as the primary source of water for farming, while a significant proportion depended on rainfall. This indicates the prevalence of water scarcity in smallholder farming systems, which limits crop diversity and reduces yields (Ricciardi et al., 2022). Therefore, the adoption of drought-tolerant crops, such as neglected legumes, into their cropping systems would enhance resilience to water stress and contribute to higher yields, thereby promoting agricultural sustainability in the face of climate variability.

4.4.2 Overview of Cropping Practices in the Surveyed Region

The results revealed that a significant proportion (87%) primarily focused on vegetable cultivation, followed by cereals, while a smaller proportion of farmers engage in legume farming. This suggests that smallholder farmers prioritize vegetable cultivation due to its economic viability, short production cycles, and high market demand. Cereals are grown for food security, while legumes are cultivated in smaller proportions due to lower profitability and longer growth durations. The balance between these crop categories reflects a strategic adaptation to market dynamics, food needs, and agronomic constraints. Similar findings were reported by Ojiewo et al. (2015) and Mkhize et al. (2022), who highlighted that vegetable production and consumption serve as a potent mechanism for disadvantaged smallholder farmers to obtain essential nutrients in their diets while generating much-needed income through trade. This underscores the need to improve market access for neglected legumes, which play a crucial role in diversifying farm incomes, and improving dietary nutrition. Strengthening legume value chains through better infrastructure, policy support, and farmer incentives could enhance their adoption, contributing to both economic resilience and sustainable agricultural systems.

In addition, the study findings revealed that nearly half of the farmers practice intercropping, while a significant proportion continue to rely on monoculture. The limited cultivation of neglected legumes has contributed to the dominance of a monoculture vegetable cropping system, as noted by Mkhize et al. (2022). However, this practice presents significant agronomic and ecological challenges, as continuous monocropping depletes soil nutrients, reduces overall crop productivity, and affects long-term agricultural sustainability (Belete and Yadete, 2023). Therefore, the findings suggest that the current monocropping system of vegetables and maize in the study area requires modification, as it leads to declining soil fertility, reduced yields, and unsustainable food and nutrition security. Furthermore, the lack of crop diversification exacerbates the risk of micronutrient deficiencies, negatively impacting dietary quality and resilience to climate variability. To promote agricultural sustainability and improve farmers' livelihoods, the integration of neglected legumes into cropping systems through intercropping and crop rotation should be promoted.

Furthermore, the small proportion of farmers cultivating legumes indicated that January is the most suitable planting period due to reduced rainfall during this time. In contrast, excessive rainfall in December often leads to pod abortion and seed rot, making this period less favourable for legume cultivation in the region. This finding suggests that farmers primarily rely on their experiential knowledge to determine optimal planting dates. However, results from neglected legumes trial demonstrations revealed that rainfall patterns in the region are increasingly erratic. Some of the neglected legume varieties introduced in the study exhibited stable performance throughout November, December, and January, challenging traditional perceptions of planting suitability. These findings highlight the need for evidence-based agronomic recommendations to help farmers adapt to changing climatic conditions and maximize neglected legumes productivity. Strengthening extension services and promoting climate-resilient, neglected legume varieties could enhance adoption rates, improve farm productivity, and contribute to diversified and sustainable cropping systems.

4.4.3 Training Participation and Knowledge of Legumes in the Surveyed Region

The results of the study revealed that only 20.7% of farmers had participated in legume training prior to the study. This suggests that the limited production of neglected legumes in the region could be attributed to the shortage of targeted training programs and extension services focused on these crops. As a result, the lack of specialized training hinders farmers' knowledge of best agronomic practices and the potential benefits of integrating neglected legumes into existing cropping systems. This was further confirmed by an assessment of farmers' knowledge of legumes in the surveyed region, which showed that 85.3% to 94.7% of farmers lacked awareness of neglected legume cultivars, production techniques, adaptability, and market opportunities. These findings align with those of Harouna et al. (2019), who highlighted that limited resources are not the only constraint affecting diversified cropping systems; rather, a lack of knowledge and awareness also presents a significant barrier. Consequently, these challenges contribute to the low adoption and limited cultivation of neglected legumes in the region. These findings underscore the urgent need for targeted capacity-building initiatives, including smallholder farmers training and knowledge dissemination programs. This concurs with the findings of Rutto (2016), who emphasized the importance of training programs that are inclusive of elderly and illiterate farmers. Such programs will enhance farmers' understanding of neglected legumes, improve their adoption, and ultimately promote food security in smallholder farming systems.

4.4.4 Pre- and Post-Training Knowledge Levels of Smallholder Farmers on the Benefits of Neglected Legumes

Prior to the study training, the findings revealed that most farmers had extensive knowledge of the nutritional richness of neglected legumes, including their high content of proteins, carbohydrates, fibre, minerals, vitamins, and micronutrients. This awareness may be attributed to information disseminated by health facilities, which emphasized the dietary importance of these foods in addressing malnutrition and highlighted the role of legumes as an alternative protein source to meat, as noted in face-to-face interviews. In contrast, between 76% and 94% of respondents were unaware of the additional benefits of neglected legumes, including their potential to reduce the risk of heart disease, diabetes, cancer, and obesity; enhance soil fertility through biological nitrogen fixation; break pest and disease cycles; conserve soil moisture; and promote ecosystem stability in marginal environments. However, following the training provided in the study, a significant proportion (81%) of farmers demonstrated a strong understanding of neglected legumes. These findings validate the effectiveness of the training, highlighting its potential to enhance farmers’ knowledge and improve the adoption of neglected legumes, thereby contributing to both nutritional security and sustainable agricultural practices. Furthermore, these findings corroborate the findings of Pui et al. (2022) and Odeku et al. (2024), who reported that a lack of awareness and knowledge regarding the nutritional and health benefits associated with consuming a diverse range of neglected legumes has contributed to limited demand, subsequently limiting their cultivation and distribution.

4.4.5 Farmers' Participation in Neglected Legume Training, Adoption Willingness, and Post-Training Cropping System Integration

The study's findings revealed that a significant proportion (92%) of respondents participated in the training on neglected legumes, which was conducted as part of this research. Following the training and trial demonstrations, most farmers (96%) expressed a willingness to integrate legumes into their cropping systems. Smallholder farmers who previously practiced monoculture showed increased interest in adopting intercropping. This suggests that targeted training and practical demonstrations play a crucial role in enhancing farmers' awareness and adoption of integrating neglected legumes. The findings highlight the potential for knowledge-based interventions to influence cropping decisions, improve crop diversification, and promote sustainable agricultural practices, as stated by Gayathri and Manimozhi (2024). Furthermore, the increased adoption of intercropping with legumes could contribute to enhanced soil fertility, improved pest and disease management, and increased resilience to climate variability in the study area. This finding aligns with the results of Kumawat et al. (2022) and Akchaya et al. (2025), who also reported the role of legume intercropping in sustainable farming systems. The findings underscore the need for continued extension support and policy initiatives to facilitate the large-scale adoption of neglected legumes.

4.4.6 Socio-Economic Factors Influencing Farmers' Willingness to Cultivate Neglected Legumes

The findings on the socioeconomic factors influencing smallholder farmers' willingness to cultivate neglected legumes, analysed through a multivariate probit regression model, revealed that training on legumes is a statistically significant determinant. Particularly, participation in training was positively correlated with the adoption of pigeon pea ($\beta = 0.479$, $P < 0.1$) and cowpea ($\beta = 0.276$, $P < 0.05$). These results suggest that farmers who received training were more inclined to adopt these neglected legumes, underscoring the crucial role of knowledge dissemination in raising awareness, improving agronomic practices, and promoting their cultivation. These findings are consistent with those of Mkhize et al. (2023), who introduced innovative cultivation and consumption methods to enhance farmers' knowledge and acceptance of cowpea and jugo beans. Their study demonstrated that educational interventions led to a statistically significant increase in both the acceptability and cultivation of these legumes. These findings underscore the crucial role of knowledge dissemination in facilitating the reintroduction of neglected legume species into local cropping systems, thereby enhancing food security, dietary diversity, and sustainable agricultural practices (Ratnayake et al., 2023).

Moreover, a positive and statistically significant relationship ($\beta = 0.140$, $P < 0.1$) was observed between marital status and cowpea adoption, indicating that farmers' marital status influences their likelihood of adopting cowpea. This suggests that married farmers may have greater access to resources, labour, or decision-making support, which could enhance their willingness to cultivate neglected legumes. Similar findings have been reported by Lana (2025) where marital status was identified as a key socioeconomic factor influencing the adoption of improved agricultural technologies and crop diversification strategies. In addition, farm size ($\beta = -0.507$, $P < 0.1$) and market access ($\beta = -0.465$, $P < 0.1$) were negatively associated with farmers' willingness to cultivate common bean, indicating that larger farm sizes and limited market access may reduce the likelihood of adopting common bean cultivation.

Conversely, access to irrigation water sources was positively correlated with the adoption of both common bean ($\beta = 0.295$, $P < 0.05$) and Bambara groundnut ($\beta = 0.270$, $P < 0.1$), suggesting that farmers with better access to irrigation are more likely to cultivate these crops. This finding highlights the significance of water availability in promoting the adoption of water-intensive crops, such as common beans, underscoring the need for improved irrigation infrastructure and enhanced market access to support smallholder farmers in diversifying their crop production systems. In contrast, the positive correlation with Bambara groundnut adoption may be attributed to its drought resistance, as demonstrated by trials conducted in the study. This resilience makes Bambara groundnut a viable option for farmers with limited access to irrigation, further highlighting the potential of drought-tolerant crops in enhancing agricultural resilience in water-scarce regions (Feldman et al., 2019; Pui et al., 2022).

4.4.7 Socio-Economic Determinants Influencing Farmers' Selection of Optimal Planting Dates

The study results revealed that socioeconomic determinants, including farm size ($\beta = -0.563$, $P < 0.1$) and legume training ($\beta = -0.388$, $P < 0.1$), were negatively and significantly correlated with the selection of a November planting date. This suggests that smallholder farmers and those who received legume training were less likely to plant in November. The negative correlation with farm size may indicate that smallholder farmers prefer alternative planting periods to optimize resource use, mitigate climatic risks, or align with labour availability.

Likewise, the negative association with legume training suggests that trained farmers may adopt improved agronomic practices or recommended planting schedules that deviate from a November planting date.

However, legume training was positively and significantly correlated with the selection of both a December ($\beta = 0.403$, $P < 0.1$) and January ($\beta = 0.326$, $P < 0.1$) planting date, whereas household size ($\beta = -0.019$, $P < 0.05$) exhibited a negative correlation with the selection of a November planting date. This suggests that farmers who received legume training were more likely to delay planting until December or January, potentially to align with recommended agronomic practices, o or mitigate risks associated with early-season climatic variability. Conversely, the negative correlation between household size and the selection of a November planting date implies that larger households were less inclined to plant in November, possibly due to competing labour demands for other agricultural activities or resource constraints. These findings underscore the critical role of agricultural training in shaping planting decisions.

Furthermore, access to water sources for irrigation ($\beta = 0.173$, $P < 0.1$) was positively and significantly associated with the selection of a January planting date. This association may be attributed to the improved performance of the neglected legumes introduced in the study under rainfed conditions, highlighting the need to adopt climate-smart, resilient crops such as neglected legumes in regions where water scarcity persists. Moreover, the availability of irrigation water provides farmers with greater flexibility in their planting decisions, enabling them to extend the growing season and mitigate risks associated with unpredictable rainfall patterns. These findings underscore the critical role of irrigation access in promoting the cultivation of neglected legumes, highlighting the need for targeted interventions to improve water management strategies and thereby enhance the productivity and sustainability of legume-based farming systems. These results are consistent with the findings of Mhembwe et al. (2019).

4.5 Conclusions, Recommendations and Research Directions

This study assessed the socioeconomic factors influencing farmers’ willingness to cultivate neglected legumes and their selection of suitable planting dates in South Africa, using KwaZulu-Natal Province as a case study. The findings indicate the crucial role of socioeconomic factors in shaping adoption decisions and cultivation of these crops into existing cropping systems. Consistent with previous research, the study confirms that limited access to land, water availability, market access, and marital status influence farmers' willingness to cultivate neglected legumes. Household size, participation in legume-related training, and access to irrigation water influence the selection of suitable planting dates. The findings further revealed that the limited cultivation and adoption of neglected legumes were not primarily due to resource constraints but rather a lack of awareness and knowledge regarding their nutritional and health benefits. This lack of awareness has contributed to low demand, which in turn limits the cultivation and distribution of neglected legumes. To address these challenges, the study recommends targeted capacity-building initiatives, including training programs for smallholder farmers and the dissemination of knowledge. These initiatives will enhance farmers' understanding of neglected legumes, encourage their adoption, and ultimately promote food security in smallholder farming systems. The effectiveness of such interventions was demonstrated through training and trial demonstrations conducted in this study, where a significant proportion of farmers expressed a willingness to cultivate neglected legumes into their cropping systems. Furthermore, farmers who previously practiced monoculture showed increased interest in adopting intercropping, highlighting the potential for knowledge-based interventions to influence cropping decisions.

Despite the promising results of this study, it is essential to acknowledge that, like other research studies, this article has limitations. The study specifically focused on smallholder crop farmers in Bergville. This may introduce some bias, as the sample comprised crop farmers affiliated with the Farmers Support Group in the region. However, this study attempted to mitigate bias by using a multistage sampling strategy to ensure representation of diverse demographic groups, particularly resource-constrained farmers actively engaged in various farming practices. Moreover, the study employed techniques to enhance data accuracy and reliability, including the use of multiple question formats to capture comprehensive information and minimize response errors. Despite these limitations, the study contributes to a deeper understanding of how socioeconomic factors, including farm size, training on legumes, marital status, household size, water sources for irrigation, and market access, influence smallholder farmers' willingness to cultivate neglected legumes and their selection of suitable planting dates.

Further research should explore the long-term impact of knowledge-based interventions on the sustained adoption of neglected legumes in smallholder farming systems. Furthermore, future studies should also examine the role of policy support, market incentives, and climate resilience in promoting their integration. Research into the genetic improvement of these legumes to enhance yield potential, adaptability, and nutritional value could further increase their appeal to both farmers and consumers. Addressing these research gaps will contribute to more resilient and diversified cropping systems, ultimately enhancing food and nutritional security while increasing the adaptability of smallholder farmers to climate variability and market dynamics.

References

1. Abberton, M., Paliwal, R., Faloye, B., Marimagne, T., Moriam, A. and Oyatomi, O., 2022. Indigenous African orphan legumes: Potential for food and nutrition security in SSA. Frontiers in Sustainable Food Systems, 6, p.708124.

2. Akchaya, K., Parasuraman, P., Pandian, K., Vijayakumar, S., Thirukumaran, K., Mustaffa, M.R.A.F., Rajpoot, S.K. and Choudhary, A.K., 2025. Boosting resource use efficiency, soil fertility, food security, ecosystem services, and climate resilience with legume intercropping: a review. Frontiers in Sustainable Food Systems, 9, p.1527256.

3. Belete, T. and Yadete, E., 2023. Effect of mono cropping on soil health and fertility management for sustainable agriculture practices: A review. Plant Sci, 11, pp.192-197.

4. Bless, C., Higson-Smith, C. and Kagee, A., 2006. Fundamentals of social research methods: An African perspective. Juta and Company Ltd.

5. Chipfupa, U. and Tagwi, A., 2021. Youth's participation in agriculture: A fallacy or achievable possibility? Evidence from rural South Africa. South African Journal of Economic and Management Sciences, 24(1), pp.1-12.

6. Danquah, E.O., Frimpong, F., Addo-Danso, A., Amankwaa-Yeboah, P., Yeboah, S., Danquah, F.O., Dankwa, K.O., Aidoo, K.A.S., Keteku, A.K., Asante, M.O.O. and Tetteh, E.N., 2025. Climate-smart cropping systems for resilient food production in Sub-Saharan Africa in the face of changing climate: a review. Circular Agricultural Systems, 5(1).

7. Department of Agriculture, Land Reform and Rural Development (DALRRD)., 2020. Dry Bean Value Chain Profile 2020. Pretoria: Directorate Marketing. Available at: https://www.dalrrd.gov.za

8. Dhanaraj, A., Girdhar, S. and Prakash, P., 2024. Transformative Education: A Strategical Tool for Empowering Social Change and Sustainable Future in the Indian Context. Library of Progress-Library Science, Information Technology & Computer, 44(3).

9. Dixon, J., Garrity, D.P., Boffa, J., Williams, T.O., Amede, T., Auricht, C., Lott, R. and Mburathi, G., 2020. Farming systems and food security in Africa. J. Dixon, DP Garrity, J.-M. Boffa, TO Williams, & T. v (Eds.), Priorities for science and policy under global change.

10. FAO., 2017. The State of Food and Agriculture: Leveraging food systems for inclusive rural transformation. Food and Agriculture Organization of the United Nations

11. Feldman, A., Ho, W.K., Massawe, F. and Mayes, S., 2019. Bambara groundnut is a climate-resilient crop: how could a drought-tolerant and nutritious legume improve community resilience in the face of climate change? Sustainable solutions for food security: Combating climate change by adaptation, pp.151-167.

12. Foguesatto, C.R., Borges, J.A.R. and Machado, J.A.D., 2020. A review and some reflections on farmers' adoption of sustainable agricultural practices worldwide. Science of the total environment, 729, p.138831.

13. Gayathri, M. and Manimozhi, K., 2024. Bridging the Knowledge Gap: Enhancing Awareness among Farmers about Millet Cultivation. Current Agriculture Research Journal, 12(1).

14. Ge, Y., Fan, L., Li, Y., Guo, J. and Niu, H., 2023. Gender differences in smallholder farmers’ adoption of crop diversification: Evidence from Shaanxi Plain, China. Climate Risk Management, 39, p.100482.

15. Geza, W., Ngidi, M., Ojo, T., Adetoro, A.A., Slotow, R. and Mabhaudhi, T., 2021. Youth participation in agriculture: A scoping review. Sustainability, 13(16), p.9120.

16. Glazebrook, T., Noll, S. and Opoku, E., 2020. Gender matters: Climate change, gender bias, and women’s farming in the global South and North. Agriculture, 10(7), p.267.

17. Harouna, D.V., Venkataramana, P.B., Matemu, A.O. and Ndakidemi, P.A., 2019. Wild Vigna legumes: farmers’ perceptions, preferences, and prospective uses for human exploitation. Agronomy, 9(6), p.284.

18. Hlatshwayo, S.I., Ngidi, M., Ojo, T., Modi, A.T., Mabhaudhi, T. and Slotow, R., 2021. A typology of the level of market participation among smallholder farmers in South Africa: Limpopo and Mpumalanga Provinces. Sustainability, 13(14), p.7699.

19. Hossain, A., Islam, M.T., Maitra, S., Majumder, D., Garai, S., Mondal, M., Ahmed, A., Roy, A., Skalicky, M., Brestic, M. and Islam, T., 2021. Neglected and underutilized crop species: are they future smart crops in fighting poverty, hunger and malnutrition under changing climate? Neglected and underutilized crops-towards nutritional security and sustainability, pp.1-50.

20. Kebede, E., 2020. Grain legumes production and productivity in Ethiopian smallholder agricultural system, contribution to livelihoods and the way forward. Cogent Food & Agriculture, 6(1), p.1722353.

21. Kumawat, A., Bamboriya, S.D., Meena, R.S., Yadav, D., Kumar, A., Kumar, S., Raj, A. and Pradhan, G., 2022. Legume-based inter-cropping to achieve the crop, soil, and environmental health security. In Advances in legumes for sustainable intensification (pp. 307-328). Academic Press.

22.Lana, M., 2025. Exploring gender dynamics in climate-smart agriculture adoption: a study in semi-arid Dodoma, Tanzania.

23. Li, X., Yadav, R. and Siddique, K.H., 2020. Neglected and underutilized crop species: the key to improving dietary diversity and fighting hunger and malnutrition in Asia and the Pacific. Frontiers in Nutrition, 7, p.593711.

24. Mhembwe, S., Chiunya, N. and Dube, E., 2019. The contribution of small-scale rural irrigation schemes towards food security of smallholder farmers in Zimbabwe. Jàmbá: Journal of Disaster Risk Studies, 11(1), pp.1-11.

25. Mihrete, T.B. and Mihretu, F.B., 2025. Crop Diversification for Ensuring Sustainable Agriculture, Risk Management and Food Security. Global Challenges, p.2400267.

26. Mkhize, X., Napier, C., Oldewage-Theron, W. and Duffy, K., 2023. Educating Urban Farmers in Kwazulu-Natal, South Africa on New Innovative Ways of Reintroducing Cowpea (Imbumba) and Jugo Beans (Izindlubo) to Remodel Their Production and Consumption Patterns. Indilinga African Journal of Indigenous Knowledge Systems, 22(1), pp.90-108.

27. Mkhize, X., Oldewage-Theron, W., Napier, C., Duffy, K. and Mthembu, B.E., 2022. Introducing grain legumes for crop diversification and sustainable food production systems amongst urban small-holder farmers: a food and nutrition security project in KwaZulu-Natal, South Africa. Agroecology and Sustainable Food Systems, 46(6), pp.791-814.

28. Mkuhlani, S., Crespo, O., Rusere, F., Zhou, L. and Francis, J., 2020. Classification of small-scale farmers for improved rainfall variability management in South Africa. Agroecology and Sustainable Food Systems, 44(1), pp.7-29.

29. Mrabet, R., 2023. Sustainable agriculture for food and nutritional security. In Sustainable agriculture and the environment (pp. 25-90). Academic Press.

30. Mukaila, R., Falola, A. and Omotesho, O.A., 2021. Food security status: its drivers and coping strategies among vegetable farming households.

31. Mulaudzi, A.I., Olorunfemi, O.D. and Agholor, A.I., 2024. Social media utilization level among South African smallholder farmers: a case study of Mopani District, Limpopo Province. Cogent Social Sciences, 10(1), p.2356722.

32. Nkansah-Dwamena, E., 2024. Why small-scale circular agriculture is central to food security and environmental sustainability in sub-saharan Africa? The case of Ghana. Circular Economy and Sustainability, 4(2), pp.995-1019.

33. Nyambo, P., Nyambo, P., Mavunganidze, Z. and Nyambo, V., 2022. Sub-Saharan Africa smallholder farmers agricultural productivity: risks and challenges. In Food security for African smallholder farmers (pp. 47-58). Singapore: Springer Nature Singapore.

34. Odeku, O.A., Ogunniyi, Q.A., Ogbole, O.O. and Fettke, J., 2024. Forgotten gems: exploring the untapped benefits of underutilized legumes in agriculture, nutrition, and environmental sustainability. Plants, 13(9), p.1208.

35. Ojiewo, C., Keatinge, D.J., Hughes, J., Tenkouano, A., Nair, R., Varshney, R., Siambi, M., Monyo, E., Ganga-Rao, N.V.P.R. and Silim, S., 2015. The role of vegetables and legumes in assuring food, nutrition, and income security for vulnerable groups in Sub-Saharan Africa. World Medical & Health Policy, 7(3), pp.187-210.

36. Osabohien, R., Wiredu, A.N., Nguezet, P.M.D., Mignouna, D.B., Abdoulaye, T., Manyong, V., Bamba, Z. and Awotide, B.A., 2021. Youth participation in agriculture and poverty reduction in Nigeria. Sustainability, 13(14), p.7795.

37. Pradhan, A., S, R., DJ, N., Panda, A.K., Wagh, R.D., Maske, M.R. and RV, B., 2021. Farming system for nutrition-a pathway to dietary diversity: evidence from India. Plos one, 16(3), p.e0248698.

38. Pui, L.P., Tan, W.C., Kong, I. and Tan, C.H., 2022. Drought-tolerant Bambara groundnuts as future food: a comprehensive review of its properties and applications in food. British Food Journal, 124(11), pp.3680-3694.

39. Ratnayake, S., Reid, M., Hunter, D., Larder, N., Silva, R., Kadupitiya, H., Pushpakumara, G., Borelli, T., Mendonce, S., Liyanage, A. and Samarasinghe, G., 2023. Exploring social-ecological systems for mainstreaming neglected and underutilised plant foods: local solutions

to food security challenges in Sri Lanka. In Neglected Plant Foods of South Asia: Exploring and Valorizing Nature to Feed Hunger (pp. 171-225). Cham: Springer International Publishing.

40. Ricciardi, V., Wane, A., Sidhu, B.S., Godde, C., Solomon, D., McCullough, E., Diekmann, F., Porciello, J., Jain, M., Randall, N. and Mehrabi, Z., 2020. A scoping review of research funding for small-scale farmers in water scarce regions. Nature Sustainability, 3(10), pp.836-844.

41. Rosa-Schleich, J., 2023. Diversified Farming Systems–An evaluation of ecological benefits, economic costs & risks farmers face.

42. Rutto, S.K., 2016. Factors influencing involvement of legume farmers in agricultural training programs in Makueni County, Kenya (Doctoral dissertation, University Of Nairobi).

43. Saliu, F., Luqman, M. and Alkhaz'leh, H.S., 2023. A review on the impact of sustainable agriculture practices on crop yields and soil health. International Journal of Research and Advances in Agricultural Science, 2(3), pp.1-13.

44. Samal, I., Bhoi, T.K., Raj, M.N., Majhi, P.K., Murmu, S., Pradhan, A.K., Kumar, D., Paschapur, A.U., Joshi, D.C. and Guru, P.N., 2023. Underutilized legumes: nutrient status and advanced breeding approaches for qualitative and quantitative enhancement. Frontiers in Nutrition, 10, p.1110750.

45. Schling, M. and Pazos, N., 2024. Effective land ownership, female empowerment, and food security: Evidence from Peru. World Development, 181, p.106680.

46. Sharma, P., Tailor, A., Joshi, A. and Bhoi, T.K., 2024. Genetic diversity of grain legumes for food and nutritional security. In Sustainable Utilization and Conservation of Plant Genetic Diversity (pp. 63-105). Singapore: Springer Nature Singapore.

47. Sithole, A. and Olorunfemi, O.D., 2024. Sustainable agricultural practices in Sub-Saharan Africa: a review of adoption trends, impacts, and challenges among smallholder farmers. Sustainability (2071-1050), 16(22).

48. Stringer, E.T. and Aragón, A.O., 2020. Action research. Sage publications.

49. Terefe, D., 2025. Enhancing Youth Engagement in Agriculture for a Sustainable Future in Ethiopia: Challenges and Policy Solutions in Focus.

50. Touch, V., Tan, D.K., Cook, B.R., Li Liu, D., Cross, R., Tran, T.A., Utomo, A., Yous, S., Grunbuhel, C. and Cowie, A., 2024. Smallholder farmers' challenges and opportunities:

Implications for agricultural production, environment and food security. Journal of Environmental Management, 370, p.122536.

51. Vilakazi, B., Mafongoya, P.L., Odindo, A.O. and Phophi, M.M., 2025. The role of neglected grain legumes in food and nutrition security and human health. sustainability, 17(1), p.350.

52.Vilakazi, B.S., Zengeni, R. and Mafongoya, P., 2019. Indigenous strategies used by selected farming communities in KwaZulu Natal, South Africa, to manage soil, water, and climate extremes and to make weather predictions. Land Degradation & Development, 30(16), pp.1999-2008.

53. Wijerathna-Yapa, A. and Pathirana, R., 2022. Sustainable agro-food systems for addressing climate change and food security. Agriculture, 12(10), p.1554.

54. Yamane, T., 1973. Statistics: An Introductory Analysis. New York: Harper and Row.

Chapter 5: Effect of Planting Date on Agronomic Performance of Neglected Legumes Under Rainfed Conditions

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Abstract

Neglected legumes have significant potential to enhance food security, improve soil fertility, and increase climate resilience, particularly in smallholder rain-fed farming systems. Despite their agronomic value, limited information exists on their performance under varying planting dates. This study examined the effect of planting date on the agronomic performance of neglected legume crops, including Bambara groundnut (*Vigna subterranea*), cowpea (*Vigna unguiculata*), pigeon pea (*Cajanus cajan*), and common bean (*Phaseolus vulgaris*) under rainfed conditions. Field trials were conducted over two consecutive summer growing seasons (2022/23 and 2023/24) using a split-plot randomized complete block design with three replications. Phenological traits (emergence, flowering, podding, and senescence) and yield component (pod mass, and grain yield) were recorded and analysed using GenStat® and principal component analysis. Significant effects of planting date, legume species, season, and their two- and three-way interactions ($P \leq 0.05$) were observed for all measured traits. Early planting improved crop establishment and vegetative growth across all legume species, particularly in cowpea and Bambara groundnut, which exhibited high emergence rates (90.2% and 85.6%, respectively) and stable phenological development across planting dates and seasons. However, reproductive performance varied among species, depending on the synchronization of flowering and podding with rainfall and temperature patterns. Delayed planting enhanced grain yield in common bean, cowpea, and Bambara groundnut, while pigeon pea showed reduced reproductive success under late sowing due to its sensitivity to shortened growing periods. These findings underscore the importance of aligning planting dates with species-specific phenological responses, using seasonal climate forecasts and local weather information to guide sowing decisions. Integrating climate-informed planning can help optimise the productivity and resilience of neglected legumes in rainfed systems under increasing climate variability.

Keywords: Phenology, yield components, underutilized crops, rainfed agriculture, smallholder farming, optimal planting date, PCA

5.1 Introduction

Neglected legumes, also referred to as orphan or underutilized crops, have garnered increasing attention in recent years due to their potential contributions to food security, dietary diversification, and the sustainability of agricultural systems, particularly in regions susceptible to climate variability (Odeku et al., 2024; Kimani et al., 2025). Species such as cowpea (*Vigna unguiculata*), pigeon pea *(Cajanus cajan*), Bambara groundnut (*Vigna subterranea*), tepary bean (*Phaseolus acutifolius*), marama bean (*Tylosema esculentum*), rice bean (*Vigna umbellata*), and moth bean (*Vigna aconitifolia*) remain largely underrepresented in mainstream agricultural research and development (Popoola et al., 2020; Vilakazi et al., 2025). In contrast, major legumes, including soybean (*Glycine max*), groundnut (*Arachis hypogaea*), common bean (*Phaseolus vulgaris*), and chickpea (*Cicer arietinum*), have benefited from substantial scientific and commercial investment (Sheoran et al., 2022; Ikhajiagbe et al., 2022). Neglected legumes are often native to specific agroecological zones, exhibiting high levels of adaptation to local environmental conditions. They are particularly well-suited to cultivation in marginal environments characterized by low soil fertility, limited rainfall, and other abiotic stresses typical of rainfed systems (Wani et al., 2021; Odeku et al., 2024; Ilić et al., 2025). Nutritionally, these species are valuable sources of plant-based protein, essential amino acids, and micronutrients, and they play a crucial role in the diets of populations in regions where access to animal-derived proteins is limited (Odeku et al., 2024; Vilakazi et al., 2025).

Popoola et al. (2020) state that these neglected legumes also offer significant agroecological benefits, primarily due to their ability to fix atmospheric nitrogen through symbiotic associations with rhizobia bacteria (Kebede, 2021; Jena et al., 2022; Gou et al., 2023). This process enhances soil fertility, reduces reliance on synthetic nitrogen fertilizers, and contributes to more sustainable nutrient cycling within cropping systems. These legumes enhance the productivity of subsequent crops in rotation, thereby reinforcing their agronomic value in low-input and conservation agriculture systems (Kuyah et al., 2021; Islam et al., 2023). Their integration into smallholder farming systems is particularly beneficial, as they simultaneously support dietary protein intake and promote ecosystem services such as soil health and biodiversity conservation (Ditzler et al., 2021; (Farooq et al., 2023; Rasheed and Azeem, 2024). However, despite their adaptability to marginal environments and socio-cultural significance, the broader utilization of neglected legumes is hindered by minimal genetic improvement, limited agronomic characterization, and poor integration into formal seed systems and commercial markets (Popoola et al., 2020; Knez et al., 2023; Zafar et al., 2024). These constraints continue to impede their inclusion in mainstream agricultural research and development initiatives (Knez et al., 2023).

In rainfed agricultural systems characterized by reliance on precipitation and increased vulnerability to erratic rainfall patterns, temperature fluctuations, and climate-induced stresses, neglected legumes offer a strategic opportunity to diversify cropping systems and enhance resilience (Mabhaudhi et al., 2022; Farooq et al., 2023). These species are well-adapted to suboptimal growing conditions and can achieve acceptable yields in environments where irrigation is not feasible, making them particularly valuable for improving food and nutritional security in smallholder farming systems across semi-arid and sub-humid regions (Mampholo et al., 2024). Among the key determinants of crop productivity under rainfed conditions, planting date is critical, as it directly influences crop establishment, growth dynamics, and final yield (Bateman et al., 2020). Determining the optimal sowing time under variable rainfall conditions requires adaptive approaches rather than fixed planting dates. In this context, strategies such as staggered planting and the use of seasonal climate forecasts enable farmers to align crop phenology with periods of favourable soil moisture and temperature conditions each season. Such adaptive timing enhances resource use efficiency while mitigating the risks of yield losses caused by terminal drought, heat stress, or disease outbreaks (Shah et al., 2020; Khatun et al., 2021).While the influence of planting date has been extensively documented in major staple crops, empirical data on its effects in neglected legume species remain scarce, particularly under rainfed conditions where water availability is inherently variable. Consequently, the agronomic responses of these legumes to sowing time and other key management practices remain poorly characterized, limiting the development of evidence-based recommendations to optimize their production in marginal environments. This lack of agronomic data constrains efforts to optimize productivity, support adoption among smallholder farmers, and fully integrate these crops into diversified, climate-resilient farming systems. The challenge is particularly pronounced in rainfed agricultural regions, which predominate in sub-Saharan Africa and other semi-arid zones.

In the absence of crop-specific agronomic guidelines, many farmers rely on generalized planting calendars or inherited traditional practices that may not adequately reflect current climatic conditions. For neglected legumes, there is a critical need for empirical data on the impact of planting time on crop performance under rainfed conditions. This study was conducted in Bergville, South Africa, a representative site for rainfed smallholder farming systems. It aims to address critical knowledge gaps by evaluating the effects of varying planting dates on the agronomic performance of three neglected legume species, cowpea (*Vigna unguiculata*), Bambara groundnut (*Vigna subterranea*), pigeon pea (*Cajanus cajan*), and common bean (*Phaseolus vulgaris*) under rainfed conditions. The primary objective was to identify optimal sowing dates that align with local rainfall patterns and temperature regimes, thereby maximizing crop productivity and contributing to the sustainability of rainfed smallholder farming systems. It was hypothesized that early planting would enhance crop emergence, growth, and yield by synchronizing crop development with the onset of seasonal rainfall, whereas delayed planting would negatively impact performance due to increased exposure to terminal drought stress. Agronomic traits assessed included emergence rate, time to flowering, podding, senescence, and grain yield. These parameters were selected for their relevance as key indicators of crop adaptation, developmental plasticity, and yield potential under variable climatic conditions. The findings are expected to inform climate-resilient cropping strategies and support the broader integration of neglected legumes into sustainable and diversified agricultural systems.

5.2 Materials and methods

5.2.1 Experimental Site Description

The study was conducted over two consecutive summer growing seasons (2022/2023 and 2023/2024) in Bergville, located in the KwaZulu-Natal Province of South Africa, as outlined in chapter 3 and 4. The first season (2022/2023) was conducted at Site 1, and the second season (2023/2024) at Site 2, representing two sites within the study area.

5.2.2 Experimental design and layout

The experiment was conducted using a split-plot arrangement within a Randomised Complete Block Design (RCBD) to facilitate efficient management of harvesting and data collection across different planting dates. The primary factor in the main plot was planting date, with three levels: November, December, and January. The subplot factor was legume species, comprising four legume species: Bambara groundnut (*Vigna subterranea*), cowpea (*Vigna unguiculata*), pigeon pea (*Cajanus cajan*), and common bean (*Phaseolus vulgaris*). Each main plot (planting date) was subdivided into subplots representing the respective medium duration legume species. There were three replications for each planting date and species. Each plot measured 4 × 4 m^2. The experimental area was prepared using a disc plough. Seeds were sown manually using a hand dibber at a depth of 5 cm. Intra- and inter-row spacing varied by legume crop: common bean (15 × 40 cm), Bambara groundnut (10 × 50 cm), pigeon pea (30 × 60 cm), and cowpea (30 × 60 cm). Two seeds were sown per hole and thinned to one plant per stand 15 days after emergence. Pigeon pea, cowpea, and common bean were planted in furrows, whereas Bambara groundnut was planted on mounded ridges. The ridges for Bambara groundnut were constructed four weeks after sowing. All plots were managed under rainfed conditions without supplemental irrigation to simulate typical smallholder farming systems. No chemical fertilizers or soil amendments were applied during the trial period. Weed control was conducted manually at regular intervals. To manage pest pressure, all plots were treated with Karate® (lambda-cyhalothrin) insecticide targeting stink bugs (*Chinavia hilaris and Euschistus servus*), beetles (*Coleoptera spp.*), and aphids (*Aphididae spp.*).

5.2.3 Data collection

5.2.3.1 Climate data

Table 5.1: Rainfall and temperature distribution during the 2022/2023 and 2023/2024 growing seasons (October–January) in Bergville, KwaZulu-Natal, South Africa.

	Rainfall (mm/month)		**Min Temperature (°C)**		**Max Temperature (°C)**	
Month	**S1**	**S2**	**S1**	**S2**	**S1**	**S2**
October	148	115	11,4	11	25,5	26
November	196	104	13,6	12	26,7	26
December	295	200	15,2	14	28,3	27
January	291	312	16,2	14,9	29,3	25,5

Note that **S1** indicates Season 1(2022/23), **S2**; Season 2 (2223/24)

Meteorological data, including rainfall and temperature, were sourced from the https://www.weather2visit.com/africa/south-africa/bergville.htm website which provides comprehensive climatic information for Bergville, KwaZulu-Natal, South Africa (Table 5.1). The meteorological data for 2022/2023 and 2023/2024 growing seasons (October to January) reveal notable interannual variations in both temperature and precipitation. The first season (2022/2023) exhibited a consistent warming trend across the four months, with minimum temperatures increasing from 11.4°C in October to 16.2°C in January, and maximum temperatures ranging from 25.5°C to 29.3 °C. In contrast, the 2023/2024 season recorded marginally lower minimum temperatures, ranging from 11.0 °C to 14.9°C, and a subdued maximum temperature profile, peaking at 27.0°C in December before declining to 25.5°C in January. Total rainfall for the early season (October–December) was substantially lower in 2023/2024 compared to the previous year. October, November, and December 2023/2024 received 115 mm, 104 mm, and 200 mm, respectively, representing reductions of 22%, 47%, and 32% relative to the same months in 2022/2023. However, this trend was reversed in

January, with 312 mm recorded in 2023/2024, surpassing the 291 mm observed in the corresponding month of 2022/2023. These deviations suggest a comparatively cooler growing environment in 2023/2024, particularly during the reproductive phase of the legumes.

5.2.3.2 Physical properties and chemical analysis

Before the establishment of field trials, soil samples were collected from a depth of 0–20 cm at both experimental sites and submitted to the Cedara Agricultural Laboratory in Pietermaritzburg, South Africa, for analysis. Selected physical and chemical properties were evaluated to determine the baseline soil conditions at each site before planting.

Table 5.2: Physical properties and chemical analysis of two experimental sites

Parameter	**Site 1**	**Site 2**
Soil texture		
Clay %	29	48
Silt %	25	27
Sand %	36	25
Nitrogen (%)	0.10	0.17
Phosphorus (mg kg $^{-1}$)	6	2
Potassium (mg kg $^{-1}$)	144	176
Calcium (mg kg $^{-1}$)	370	549
Magnesium (mg kg^{-1})	111	180
Manganese (mg kg $^{-1}$)	12	8
Copper (mg kg $^{-1}$)	3.2	2.0
Zinc (mg kg $^{-1}$)	3.1	0.8
Organic carbon (%)	1.9	3.0
pH (KCl)	3.94	3.95

Table 5.2 summarizes the physical and chemical properties of the two experimental sites. Site 1 was classified as clay loam, containing 29% clay, 25% silt, and 36% sand, while Site 2 was classified as clay, with higher clay (48%) and silt (27%) contents and lower sand (25%). The heavier texture at Site 2 suggests greater water-holding capacity but limited drainage and aeration compared to Site 1. Chemically, Site 2 showed higher concentrations of total nitrogen (0.17% vs. 0.10%), potassium (176 vs. 144 mg kg^{-1}), calcium (549 vs. 370 mg kg^{-1}), magnesium (180 vs. 111 mg kg^{-1}), and organic carbon (3.0% vs. 1.9%), indicating higher fertility and improved potential for soil structural stability. However, both sites were strongly acidic (pH 3.94–3.95 KCl), which may restrict nutrient availability. Phosphorus levels were generally low, especially at Site 2 (2 mg kg^{-1} vs. 6 mg kg^{-1} at Site 1), while micronutrients such as manganese, copper, and zinc were more abundant at Site 1, with zinc notably deficient at

Site 2 (0.8 vs. 3.1 mg kg^{-1}). These variations suggest differences in nutrient dynamics and potential crop performance between the two sites.

5.2.3.3 Phenological traits

Phenological data were recorded from the inner two rows of each replicate to minimize border effects. Emergence was monitored through daily visual observations for 14 days following sowing. Emergence was considered complete when no new seedlings emerged and at least 90% of the final plant population had emerged.

Crop phenology was assessed by recording the number of days from sowing to flowering, podding, and leaf senescence. A phenological stage was considered to have occurred when it was observed in at least 50% of the plants within a plot. Days to podding were defined as the number of days from sowing to the appearance of the first pods on at least 50% of the plants. Days to leaf senescence were recorded as the number of days from sowing until at least 50% of the foliage had senesced, with no subsequent leaf regeneration.

5.2.3.4 Yield components

At physiological maturity, five representative plants were randomly selected from the inner two rows of each plot to determine yield components. The pod mass was used to characterize the seed yield response across the planting dates. The pods were then harvested, air-dried, and weighed using a digital precision weighing balance (with an accuracy of ±0.01 g) to determine their mass.

5.2.3.5 Grain yield determination

Grain yield was determined for cowpea, common bean, pigeon pea, and Bambara groundnut based on harvested grain from a defined net plot area. At physiological maturity, plants from the central rows of each plot, excluding border rows, were manually harvested. The harvested material was sun-dried to a constant weight, manually threshed, and the grains were weighed. Yields were then expressed in tons per hectare (t ha^{-1}), adjusted to standard moisture content. This method follows standard procedures described by Gomez and Gomez (1984) and is widely used in legume field trials under rainfed conditions.

5.2.3.6 Data analysis

Data from the two seasons (2022/2023 and 2023/24) were subjected to the analysis of variance (ANOVA) using GenStat® statistical software (14th edition). The least significant difference (LSD) test was used to compare significant differences between the treatment means for each parameter and interaction at a significance level of $P < 0.05$. Multivariate statistical analyses, including Principal Component Analysis (PCA) and correlation analysis, were performed on the data obtained.

5.3 Results

5.3.1 Effect of Planting Date on Key Phenological Stages of Legume Species

Significant differences in 90% emergence were observed among planting dates across species ($P \leq 0.05$), with significant interaction effects involving season, species, and planting date ($P \leq 0.05$) (Table 5.3). The common bean exhibited considerable variability in emergence across different planting dates and seasons. The highest emergence percentage was recorded in Season 1 at Planting Date 3 (S1 PD3; 92.4%), while the lowest occurred in Season 2 at the same planting date (S2 PD3; 56.7%). Pigeon pea consistently showed lower emergence percentages than the other legumes, particularly during Season 2. Emergence declined from 84.0% (S1 PD1) to 40.5% (S2 PD3). In contrast, cowpea demonstrated relatively stable and high emergence across all planting dates and both seasons, with values ranging from 68.2% (S1 PD2) to 85.6% (S2 PD3). Similarly, Bambara groundnut exhibited high emergence percentages, particularly when planted at earlier dates. Emergence peaked at 90.2% in S1 PD3 and remained consistently above 74% across Season 2. Despite its overall robust emergence, a slight decline was noted with delayed planting in the second season.

Highly significant differences in days to 50% flowering were also observed among species and planting dates ($P \leq 0.001$), accompanied by significant interaction effects for all combinations of season, species, and planting date (S × C, S × PD, C × PD, S × C × PD; all $P \leq 0.001$). Common bean flowered earliest among all tested legumes, with flowering dates ranging from 40.8 to 44.7 days. Delayed planting (PD3) appeared to slightly accelerate flowering in S1 but had a more stabilizing or even delaying effect in S2. In contrast, pigeon pea exhibited an extended vegetative phase, with flowering occurring between 156.8 and 169.5 days after planting, largely unaffected by the planting date. Cowpea maintained consistent flowering times across all treatments, ranging from 58 to 63 days, with marginally earlier flowering observed in PD1. Bambara groundnut flowered between 48.2 and 52.4 days after planting, showing minimal sensitivity to the planting date.

No significant interaction between species and planting date was observed for days to 50% podding; however, highly significant two-way interactions were detected ($P \leq 0.05$). Common bean podded relatively early, between 60.7 and 64.4 days, with minor variations across seasons and planting dates. Pigeon pea required the longest duration to reach 50% podding (186.1 to

194.5 days), with limited seasonal fluctuation. Cowpea showed consistent podding across all treatments (79.4 to 81.3 days), while Bambara groundnut ranged from 67.1 to 70 days, with a slight reduction in duration under later planting dates. Senescence was significantly influenced by all main and two-way interaction effects ($P \leq 0.05$), except the three-way interaction (S × C × PD), which was not significant. The common bean reached senescence the earliest (91.9 to 95.1 days).

In contrast, pigeon pea exhibited a markedly extended growth cycle, with senescence occurring between 245.9 and 260.6 days, indicative of its indeterminate growth pattern. Cowpea showed moderate longevity, senescing between 109.2 and 114.5 days. Bambara groundnut senesced later than cowpea, with durations ranging from 123.6 to 127.6 days, reflecting its longer reproductive phase.

Table 5.3: Effect of planting date on key phenological stages of legume crops. 90% Emer; 90% emergence; D50%F = days to 50% flowering; D50%P = days to 50% podding; DS = days to Senescence

		90% Emer		**D50%F**		**D50%P**		**D50%S**	
Legume Species (LS)	**Planting date (PD)**	**S1**	**S2**	**S1**	**S2**	**S1**	**S2**	**S1**	**S2**
Common bean	1	78.4^{de}	69.8^{c}	43.4^{bc}	41.0^{ab}	60.7^{a}	63.6^{bc}	91.9^{a}	93.0^{a}
	2	56.1^{ab}	66.5^{c}	42.3^{ab}	41.1^{ab}	61.7^{ab}	61.0^{a}	93.1^{a}	93.4^{a}
	3	92.4^{g}	56.7^{ab}	40.8^{a}	44.7^{c}	60.8^{a}	64.4^{c}	95.1^{a}	94.5^{a}
Pigeon pea	1	84.0^{fg}	68.1^{c}	157.1^{i}	169.5^{k}	186.1^{g}	194.5^{i}	245.9^{f}	258.9^{h}
	2	67.1^{c}	55.3^{ab}	165.8^{j}	169.3^{k}	190.8^{h}	193.1^{hi}	258.3^{h}	260.6^{h}
	3	59.1^{b}	40.5^{a}	156.8^{i}	168.4^{k}	188.2^{g}	193.6^{i}	250.9^{g}	258.3^{h}
Cowpea	1	75.2^{d}	78.4^{de}	59.9^{fg}	57.9^{f}	80.8^{f}	79.4^{f}	109.2^{b}	110.4^{b}
	2	68.2^{c}	72.3^{d}	61.1^{gh}	59.4^{fg}	80.3^{f}	79.7^{f}	113.1^{bc}	110.6^{b}
	3	83.3^{f}	85.6^{fg}	62.8^{gh}	58.1^{f}	81.3^{f}	80.9^{f}	114.5^{c}	109.5^{b}
Bambara groundnut	1	81.1^{f}	75.3^{d}	50.2^{de}	52.4^{e}	68.7^{de}	69.5^{de}	123.6^{de}	126.8^{e}
	2	79.1^{e}	74.2^{d}	50.1^{de}	50.1^{de}	69.9^{e}	67.1^{d}	124.4^{e}	120.4^{d}
	3	90.2^{g}	79.1^{e}	50.9^{de}	48.2^{d}	69.2^{de}	68.3^{de}	127.6^{e}	124.3^{e}
F test	-	*		***		NS		NS	
LSD 5%	-	8.85		2.214		2.408		3.624	
Interaction									
S x LS		**		***		***		***	
S x PD		**		**		***		***	
LS x PD		*		***		NS		***	
S x LS x PD		*		***		NS		NS	

Note that *, **, *** and NS indicate $P < 0.05$, <0.01, <0,001 and not significant, respectively. Planting dates 1, 2 & 3 = November, December & January; Season 1 & 2 = 2022/23 &2023/24.

5.3.2 Effect of Planting Date on Yield of Four Legume Species

Grain yield was significantly affected by planting date, growing season, and their interactions with legume species ($P < 0.05$; Table 5.4). Cowpea consistently exhibited the highest grain yields across seasons, with superior performance under early planting (November), yielding 1.85 t ha^{-1} and 1.98 t ha^{-1} in the 2022/23 and 2023/24 seasons, respectively. Similarly, Bambara groundnut showed optimal performance under early planting conditions, producing 1.35 t ha^{-1} in 2022/23 and 1.41 t ha^{-1} in 2023/24. Common bean responded positively to delayed planting during the 2023/24 season, with the highest yield of 1.73 t ha^{-1} recorded under December planting. Conversely, pigeon pea exhibited a declining yield trend with delayed planting, particularly in the 2022/23 season, where yields declined from 1.34 t ha^{-1} under early planting to 0.61 t ha^{-1} under the latest planting date.

Table 5.4: Effect of planting date on the yield of four legume species across two consecutive growing seasons (2022/23 and 2023/24)

		Yield (t/ha)	
Legume Specie (LS)	**Planting date (PD)**	**S1**	**S2**
Common bean	1	1,25	1,18
	2	1,3	1,73
	3	1,18	1,39
Pigeon pea	1	1,34	1,25
	2	1,05	0,96
	3	0,61	0,70
Cowpea	1	1,85	1,98
	2	1,42	1,56
	3	0,98	1,12
Bambara groundnut	1	1,35	1,41
	2	1,18	1,24
	3	0,81	0,74
F test	-	*	
LSD 5%	-	1.372	
Interaction			
S x LS		**	
S x PD		**	
LS x PD		*	
S x LS x PD		*	

Note that *, **, *** and NS indicate $P < 0.05$, <0.01, <0,001 and not significant, respectively. Planting dates 1, 2 & 3 = November, December & January; Season 1 & 2 = 2022/23 &2023/24.

5.3.3 Effect of Planting Date on Pod Mass

Pod mass was significantly affected by species, planting date, and growing season ($P \leq 0.05$; Figure 5.1). All interactions were highly significant ($P \leq 0.05$). In common bean, pod mass declined progressively with delayed planting during the 2022/23 season, decreasing from 1.68

g in November to 1.53 g in December and 1.33 g in January. However, in 2023/24, a slightly different trend was observed, with the lowest pod mass recorded in November (1.23 g), followed by an increase in December (1.44 g) and a relatively stable value in January (1.40 g). In contrast, pigeon pea pod mass increased consistently with delayed planting across both seasons. In 2022/23, pod mass rose from 0.46 g (November) to 0.54 g (December) and reached a maximum of 0.83 g in January. Similarly, in 2023/24, pod mass increased from 0.38 g (November) to 0.50 g (December), peaking at 0.72 g in January. In cowpea, higher pod mass values were associated with earlier planting dates in both seasons. In 2022/23, pod mass declined from 2.67 g (November) to 2.57 g (December) and further to 2.30 g in January. A decline was observed in 2023/24, where pod mass decreased from 1.35 g in November to 1.78 g in December and 1.19 g in January. Bambara groundnut also demonstrated seasonal variability. In 2022/23, pod mass declined steadily with delayed planting, from 1.10 g (November) to 0.92 g (December) and 0.94 g (January). In contrast, during the 2023/24 season, the highest pod mass was recorded in December (1.33 g), while the November and January plantings resulted in 0.93 g and 0.88 g, respectively.

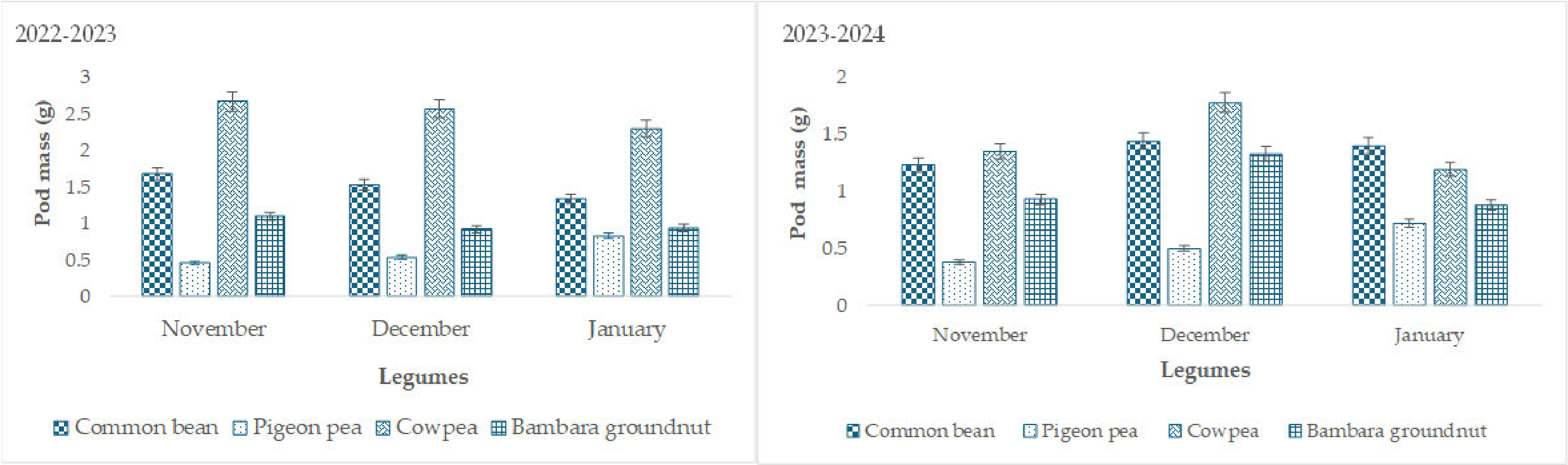

Figure 5.1: Effect of planting date on pod mass across two growing seasons (2022/23 and 2023/24).

5.3.4 Principal Component Analysis (PCA) for Assessed Traits

Table 5.5 presents the PCA with factor loadings, eigenvalues, and per cent variance for the evaluated traits. Under November planting date, PC1 contributed 89.3% of the total variance and was positively associated with DF (0.466), DP (0.465), and DS (0.468), indicating that these phenological traits were strongly correlated and represented the main source of variation. EM showed a strong negative loading (-0.434) on PC1, indicating that early emergence was associated with shorter phenological duration. PM loaded highly on PC2 (0.875), explaining an additional 7.4% of the variance and highlighting that pod mass was largely independent from phenological development under this planting time.

In the December planting, PC1 accounted for 77.3% of the total variance and was again positively associated with DF, DP, and DS, exhibiting a similar trend to that observed in the November planting. EM exhibited a negative loading (-0.284) on PC1 but was strongly and positively associated with PC2 (0.930), indicating that variation in emergence timing became more pronounced under this planting condition. PM contributed mainly to PC3 (0.844), suggesting that yield-related variability was largely distinct from phenological traits in December.

In the January planting, PC1 explained 86.0% of the total variance, with DF, DP, and DS showing strong positive loadings (0.472–0.478), confirming their close association across all planting dates. EM had a negative loading (-0.455) on PC1, maintaining an inverse relationship with later phenological stages. PM loaded highly on PC2 (0.924), explaining an additional 11.5% of the total variance, reflecting the influence of yield formation processes that were independent of phenological progression at this later planting.

The PCA overall results revealed that phenological traits (DF, DP, DS) consistently clustered together as the dominant contributors to total variability, whereas PM exhibited independent variation, particularly along the second or third components. This pattern suggests that yield expression, as represented by pod mass, was influenced by a separate set of factors from those driving phenological development, and that these relationships shifted slightly with varying planting times. Such differentiation implies that environmental conditions associated with planting date modify the coordination between growth duration and yield potential, with early sowing favouring stronger phenological control and later planting accentuating yield-related variation.

Table 5.5: Summary of factor loadings, eigenvalue, percent and cumulative variation for evaluated traits under three planting dates.

	November				**December**				**January**			
Trait	**PC1**	**PC2**	**PC3**	**PC4**	**PC1**	**PC2**	**PC3**	**PC4**	**PC1**	**PC2**	**PC3**	**PC4**
EM	-0.434	-0.368	0.810	-0.058	-0.284	0.930	0.219	-0.074	-0.455	-0.161	0.866	-0.107
DF	0.466	0.204	0.290	-0.810	0.499	0.052	0.319	-0.172	0.472	0.241	0.243	-0.690
DP	0.465	0.238	0.273	0.397	0.499	0.041	0.320	-0.565	0.472	0.248	0.225	-0.018
DS	0.468	-0.036	0.375	0.422	0.499	0.175	0.188	0.795	0.478	0.030	0.374	0.701
PM	-0.399	0.875	0.215	0.073	-0.415	-0.315	0.844	0.121	-0.345	0.924	0.015	0.143
Eigenvalue	4.466	0.368	0.166	0	3.866	0.774	0.360	0	4.302	0.573	0.125	0
Variability (%)	89.320	7.370	3.310	0	77.320	15.480	7.20	0	86.050	11.450	2.50	0
Cumulative (%)	89.320	96.690	100	100	77.320	92.800	100	100	86.050	97.50	100	100

Figure 5.2 (a–c) presents the principal component analysis (PCA) biplots showing the multivariate relationships among four legume species, Bambara groundnut, cowpea, common bean, and pigeon pea, based on key phenological traits: emergence (EM), days to flowering (DF), days to podding (DP), and days to senescence (DS). The first two principal components accounted for most of the variation, distinguishing the species according to their phenological and adaptive strategies across three planting dates.

In November planting (Figure 5.2a), cowpea and common bean exhibited rapid emergence and early flowering, reflecting short growth cycles that are suited to favourable early-season conditions. Pigeon pea aligned strongly with days to flowering and senescence, confirming its extended vegetative phase and late maturity. Bambara groundnut occupied an intermediate position, indicating asynchronous emergence and flowering relative to the other species. In December planting (Figure 5.2b), Bambara groundnut became closely associated with emergence, suggesting improved establishment under moderate stress, while cowpea and common bean maintained early reproductive transitions. The pigeon pea retained its long-duration pattern, emphasising its conservative growth strategy.

By January (Figure 5.2c), cowpea showed a positive association with podding and pod mass, suggesting reproductive stability under late planting, whereas pigeon pea remained linked to prolonged phenology. Bambara groundnut shifted away from early traits, indicating delayed emergence and flowering. Across planting dates, cowpea and common bean consistently displayed early phenological development, pigeon pea maintained a late-maturing habit, and Bambara groundnut exhibited variable associations reflecting strong phenotypic plasticity. These patterns demonstrate the Bambara groundnut’s adaptive flexibility and resilience to variable environments, supporting its potential role as a climate-resilient legume that complements both early- and late-maturing species in diversified cropping systems.

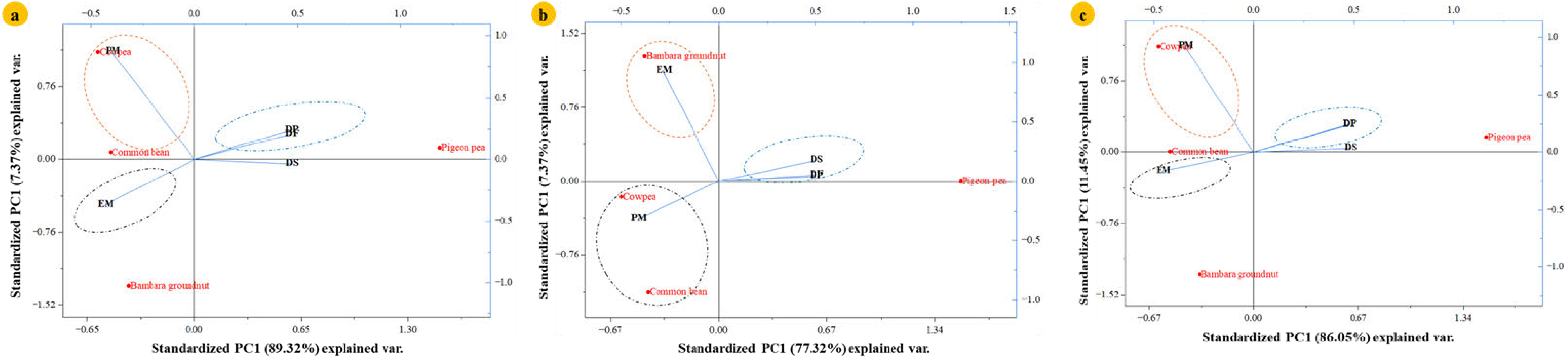

Figure 5.2: Principal Component (PC) biplots of PC1 vs PC2 illustrating the relationships between assessed traits and legume species across three planting dates: a; November, b; December & c; January. EM; emergence, DF; days to flowering, DP; days to podding, DS; days to senescence; and PM; pod mass

5.3.5 Correlation Analysis for Assessed Traits

Figure 5.3 (a–c) presents the Pearson correlation coefficients among key phenological traits, emergence (EM), days to flowering (DF), days to podding (DP), days to senescence (DS), and pod mass (PM) across three planting dates: (a) November, (b) December, and (c) January. In the November planting (Figure 5.3a), DF, DP, and DS were strongly and positively correlated ($r \geq 0.99$), indicating a high level of synchrony in the progression of reproductive development. These traits exhibited strong negative correlations with EM and PM, suggesting that prolonged crop duration was associated with reduced pod mass under early planting conditions.

In the December planting (Figure 5.3b), correlations between EM and other phenological traits weakened (r = - 0.41 to -0.49), indicating a lower dependence of later developmental stages on emergence timing. However, PM remained negatively correlated with DF, DP, and DS (r = - 0.71 to - 0.79), implying that delayed reproductive phases continued to suppress yield potential. In the January planting (Figure 5.3c), DF, DP, and DS maintained strong positive interrelationships ($r \geq 0.99$), while their correlations with EM and PM remained negative. The slightly lower magnitude of negative correlations between PM and phenological traits (r = - 0.57 to –0.69) indicates that late planting reduced the strength of the association between developmental duration and pod yield. The overall results demonstrate that as planting was delayed from November to January, the relationships among phenological traits and yield components shifted. This suggests that variations in temperature and moisture availability across planting dates influenced developmental synchrony and yield formation in the studied legume species.

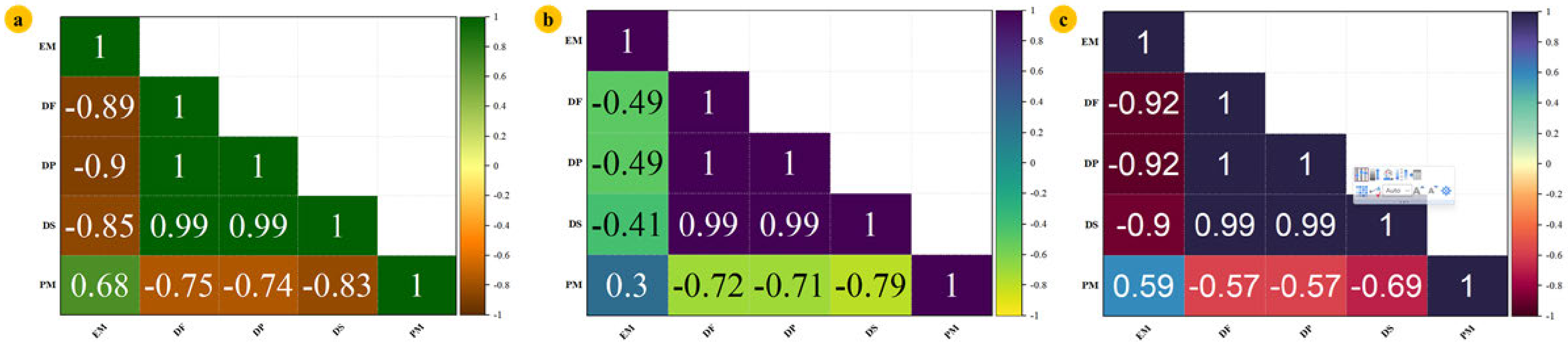

Figure 5.3: Correlations showing associations of evaluated traits under three planting dates: a (November), b (December), and c (January). EM; emergence, DF; days to flowering, DP; days to podding, DS; days to senescence; and PM; pod mass

5.4 Discussion

The study demonstrated that planting date significantly influences the phenological development of legume crops, with notable interactions involving species and seasonal variation. These findings highlight the critical role of planting date in legume production systems, particularly under rainfed or climatically variable conditions, which are typical of many smallholder farming regions. Significant variation in 90% emergence was observed across planting dates and legume species, with strong interactions with seasonal effects, emphasizing the sensitivity of initial crop establishment to planting time and prevailing environmental conditions. Common bean showed the greatest variability, with emergence ranging from 56.7% to 92.4%, suggesting a high sensitivity to temperature and soil moisture at sowing. This is consistent with previous research indicating that common bean is particularly vulnerable to suboptimal germination conditions such as low soil moisture and cooler temperatures during early or late planting dates (Lamichaney et al., 2021; Lone et al., 2021).

Cowpea and Bambara groundnut demonstrated greater emergence stability across planting dates and seasons. Bambara groundnut responded positively to early planting, with emergence rates exceeding 90% (S1 PD3), reflecting its adaptability to marginal environments and its capacity to germinate under variable soil and moisture conditions (Chimonyo et al., 2020; Obidiebube et al., 2020; Ayalew and Yoseph, 2022). Soumare et al. (2022) reported similar findings, emphasizing Bambara groundnut's resilience in poor, acidic soils. Also, Piyarathne et al. (2022) demonstrated that water deficits during cowpea seed production do not negatively impact seed germination and seedling vigor. In contrast, pigeon pea showed consistently lower emergence rates, especially during Season 2, due to climate variability, including delayed rainfall onset, rapid post-sowing soil drying, or temporary waterlogging. These environmental stresses may disproportionately affect the germination physiology of pigeon pea, particularly under acidic soil conditions, which remained consistently low with pH values of 3.94 and 3.95 in the first and second seasons, respectively. Mofokeng et al. (2022) also reported that pigeon pea emergence is more variable and sensitive across environments than other legumes used in smallholder systems.

There was significant variation in days to 50% flowering across legume species and planting dates, including all interaction terms, indicating that phenological development is closely tied to thermal time accumulation and photoperiod sensitivity. Common bean flowered earliest (40.8–44.7 days), and its accelerated flowering under delayed planting in Season 1 (PD3) suggests a potential thermal time compensation mechanism, whereby increased ambient temperatures at later sowing dates accelerate development. This aligns with findings from Bhakta et al. (2017) and González et al. (2021), who noted that common bean's flowering time is influenced by temperature and photoperiod interactions.

Pigeon pea exhibited a prolonged vegetative phase and delayed flowering (up to 169.5 days), which remained largely unaffected by planting date, consistent with its indeterminate growth habit and high photoperiod sensitivity (Helgason and Storgaard, 2023). Conversely, cowpea and Bambara groundnut showed more stable flowering durations, indicating lower photoperiod sensitivity and enhancing their adaptability across diverse production systems.

The non-significant interaction between legume species and planting date for days to 50% podding suggests consistent legume species responses in terms of reproductive initiation. However, highly significant season × species and season × planting date interactions ($P \leq 0.05$) indicate that seasonal climatic variation had a stronger influence on pod development than planting date alone. These patterns are likely to be due to inter-seasonal differences in rainfall and temperature, which affect reproductive success. Pigeon pea further exhibited the most delayed reproductive development (186.1–194.5 days), consistent with its extended growth cycle. In contrast, cowpea and Bambara groundnut podded within more moderate periods (79–82 and 67–70 days, respectively), making them well-suited for short-season production. Common bean podded earliest (60.7–64.4 days), supporting its utility in double-cropping systems or rotations with narrow production windows.

Senescence was significantly influenced by all main effects and most two-way interactions ($P \leq 0.05$), except for the three-way season × species × planting date interaction. This suggests that environmental factors substantially affect lifecycle duration, but that full interaction among these factors is less critical at maturity, likely because physiological ageing is predominantly driven by internal plant processes once reproductive development begins. Common bean reached senescence earliest (91.9–95.1 days), highlighting its suitability for short-season environments. Pigeon pea senesced latest (245.9–260.6 days), reaffirming its potential for long-season production or use as a perennial biomass and soil amelioration crop. Cowpea (109.2–114.5 days) and Bambara groundnut (123.6–127.6 days) demonstrated intermediate growth durations. The extended grain-filling period in Bambara groundnut could enhance yield under favorable late-season conditions.

Grain yield was significantly influenced by planting dates, growing season, and their interactions with legume species, underscoring the importance of planting dates in optimizing legume productivity under rainfed conditions. Cowpea consistently achieved the highest grain yields across both seasons, particularly under early planting (November), suggesting that early sowing enhances resource-use efficiency, especially in terms of moisture availability and thermal conditions during critical growth stages. This finding aligns with previous studies highlighting cowpea's early maturity and drought avoidance traits as key contributors to its superior performance under variable climatic conditions (Agbicodo et al., 2009; Ezin et al., 2021). Bambara groundnut also exhibited favorable yield responses to early planting, with stable performance across seasons. This suggests that early planting supports its extended reproductive phase and physiological adaptations to moisture stress. In contrast, common bean showed a positive yield response to delayed planting, particularly in the 2023/24 season, where improved late-season rainfall likely reduced the risk of terminal drought and supported reproductive success under December planting. Pigeon pea, however, responded negatively to delayed sowing, with yields declining markedly at later planting dates, especially in 2022/23. This decline may be attributed to pigeon pea's slow early growth and long maturity duration, which increase its exposure to intra- and inter-seasonal climatic stress when sown late. These findings highlight the necessity of species-specific planting date optimization to synchronize phenological development with favorable environmental conditions, thereby maximizing yield potential in smallholder rainfed systems.

Pod mass is the key determinant of legume yield, reflecting both sink strength and reproductive efficiency. The significant interactions observed in this study underscore the complexity of reproductive trait expression under variable environmental conditions. These results emphasize the necessity of context-specific agronomic strategies, particularly in rainfed systems where planting date is a critical management lever. In common bean, pod mass was sensitive to planting date, with trends varying across seasons. In 2022/23, delayed planting led to a progressive decline in pod mass due to increased exposure to terminal drought during pod development, which can impair assimilation availability and partitioning to developing pods, as posited by Farooq et al. (2017). However, in 2023/24, pod mass increased with delayed sowing, suggesting that later planting dates benefited from more favorable post-anthesis conditions. These opposing trends highlight the importance of aligning planting date with the seasonal onset of optimal reproductive conditions.

Pigeon pea demonstrated a contrasting pattern, with pod mass increasing consistently with delayed planting in both seasons. This suggests that later sowing allowed the crop to avoid early-season stress or benefited from improved conditions during the reproductive phase, such as adequate photo periods and temperature ranges conducive to biomass allocation toward reproductive organs, as noted by Basu et al. (2022). These findings are consistent with Singh et al. (2023), who observed increased pod development in pigeon pea when flowering and seed set occurred under moderate moisture and temperature conditions. Cowpea exhibited high pod mass, particularly at early planting dates, reaffirming its suitability for early sowing in rainfed systems. These findings are consistent with those of Ezeaku et al. (2015), who reported that early planting dates significantly enhanced reproductive development and grain yield components across all evaluated cowpea species. In 2022/23, early planting favored greater pod mass, likely due to extended pod development under favorable early-season moisture. However, in 2023/24, mid-season (December) sowing yielded the highest pod mass, suggesting better alignment of reproductive development with the rainfall pattern and thermal regime of this season. These findings agree with Soumaré et al. (2022), who reported that Bambara groundnut seed and pod development are highly responsive to intra-seasonal rainfall distribution.

5.5 Conclusion, Recommendations and Future Directions.

This study demonstrated that planting date significantly influences the agronomic performance of neglected legumes under rainfed conditions, with species-specific and seasonally variable effects on emergence, phenology, and reproductive traits such as pod mass and grain yield. Early planting consistently improved emergence and early growth across species, although reproductive responses varied. Cowpea and Bambara groundnut exhibited stable phenology and reproductive development across planting dates, highlighting their potential for inclusion in climate-smart cropping systems. In contrast, common bean showed greater sensitivity to planting date and required precise sowing to avoid stress. Due to the long growth cycle and photoperiod sensitivity of pigeon pea, it was less adaptable to delayed planting. Pigeon pea is better suited to longer-season environments or rotations focused on improvement of soil fertility. Grain yield responses were similarly nuanced, with cowpea showing the greatest stability across planting dates. These findings underscore the importance of aligning planting schedules with environmental conditions that are conducive during key phenological stages to optimize yield under rainfed conditions. The study recommends that, in rainfed smallholder farming systems characterized by climatic variability, selecting appropriate planting dates is essential for ensuring optimal crop establishment and synchronization of critical growth stages with favourable conditions.

Early planting is recommended for Bambara groundnut to capitalize on its high emergence rates and efficient early development, while common bean should be sown within a narrow optimal window to avoid suboptimal moisture or temperature stress. Cowpea’s phenological flexibility makes it suitable for staggered planting or relay cropping. Pigeon pea, given its long cycle, should be reserved for fields with a longer growing season or integrated into agroecological systems to enhance soil fertility rather than for short-season grain production. The study therefore recommends planting Bambara groundnut in December and pigeon pea in November, while cowpea and common bean are best suited to planting in either November or January. Future research should involve multi-season, multi-location trials and modelling approaches to refine planting recommendations and to investigate the physiological and molecular mechanisms underlying reproductive plasticity in neglected legumes under variable climate conditions. Physiological investigations are needed to elucidate the mechanisms underlying reproductive plasticity, particularly in cowpea and Bambara groundnut, which showed stable yields across planting dates.

References

1. Agbicodo, E.M., Fatokun, C.A., Muranaka, S., Visser, R.G. and Linden Van Der, C.G., 2009. Breeding drought tolerant cowpea: constraints, accomplishments, and future prospects. Euphytica, 167, pp.353-370.
2. Ayalew, T. and Yoseph, T., 2022. Cowpea (*Vigna unguiculata* L. Walp.): A choice crop for sustainability during the climate change periods. J. Appl. Biol. Biotechnol, 10, pp.154-162.
3. Basu, P.S., Chaturvedi, S.K., Gaur, P.M., Mondal, B., Meena, S.K., Das, K., Kumar, V., Tewari, K. and Sharma, K., 2022. Physiological mechanisms of tolerance to drought and heat in major pulses for improving yield under stress environments. In Advances in Plant Defense Mechanisms. IntechOpen.
4. Bateman, N.R., Catchot, A.L., Gore, J., Cook, D.R., Musser, F.R. and Irby, J.T., 2020. Effects of planting date for soybean growth, development, and yield in the southern USA. Agronomy, 10(4), p.596.
5. Bhakta, M.S., Gezan, S.A., Clavijo Michelangeli, J.A., Carvalho, M., Zhang, L., Jones, J.W., Boote, K.J., Correll, M.J., Beaver, J., Osorno, J.M. and Colbert, R., 2017. A predictive model for time-to-flowering in the common bean based on QTL and environmental variables. G3: Genes, Genomes, Genetics, 7(12), pp.3901-3912.
6. Chimonyo, V.G., Wimalasiri, E.M., Kunz, R., Modi, A.T. and Mabhaudhi, T., 2020. Optimizing traditional cropping systems under climate change: a case of maize landraces and Bambara groundnut. Frontiers in sustainable food systems, 4, p.562568.
7. Ditzler, L., van Apeldoorn, D.F., Pellegrini, F., Antichi, D., Bàrberi, P. and Rossing, W.A., 2021. Current research on the ecosystem service potential of legume inclusive cropping systems in Europe. A review. Agronomy for Sustainable Development, 41, pp.1-13.
8. Elsobky, E.E. and Hassan, H.H., 2021. Optimizing cowpea productivity by sowing date and plant density to mitigate climatic changes. Egyptian Journal of Agronomy, 43(3), pp.317-331.
9. Ezeaku, I.E., Mbah, B.N. and Baiyeri, K.P., 2015. Planting date and cultivar effects on growth and yield performance of cowpea (*Vigna unguiculata* (L.) Walp). African Journal of Plant Science, 9(11), pp.439-448.
10. Ezin, V., Tosse, A.G.C., Chabi, I.B. and Ahanchede, A., 2021. Adaptation of cowpea (*Vigna unguiculata* (L.) Walp.) to water deficit during vegetative and reproductive phases using physiological and agronomic characters. International Journal of Agronomy, 2021(1), p.9665312.
11. Farooq, M., Nadeem, F., Gogoi, N., Ullah, A., Alghamdi, S.S., Nayyar, H. and Siddique, K.H., 2017. Heat stress in grain legumes during reproductive and grain-filling phases. Crop and Pasture Science, 68(11), pp.985-1005.
12. Farooq, M., Rehman, A., Li, X. and Siddique, K.H., 2023. Neglected and underutilized crops and global food security. In Neglected and underutilized crops (pp. 3-19). Academic Press.
13. Gomez, K.A. and Gomez, A.A., 1984. Statistical procedures for agricultural research. John wiley & sons.
14. González, A.M., Yuste-Lisbona, F.J., Weller, J., Vander Schoor, J.K., Lozano, R. and Santalla, M., 2021. Characterization of QTL and environmental interactions controlling flowering time in Andean common bean (*Phaseolus vulgaris* L.). Frontiers in Plant Science, 11, p.599462.

15. Gou, X., Reich, P.B., Qiu, L., Shao, M., Wei, G., Wang, J. and Wei, X., 2023. Leguminous plants significantly increase soil nitrogen cycling across global climates and ecosystem types. Global change biology, 29(14), pp.4028-4043.
16. Helgason, S.B. and Storgaard, A.K., 2023. Botany of Crop Plants. In CRC Handbook of Plant Science in Agriculture (pp. 115-164). CRC Press.
17. Horn, L.N. and Shimelis, H., 2020. Production constraints and breeding approaches for cowpea improvement for drought prone agro-ecologies in Sub-Saharan Africa. Annals of Agricultural Sciences, 65(1), pp.83-91.
18. Ikhajiagbe, B., Ogwu, M.C., Ogochukwu, O.F., Odozi, E.B., Adekunle, I.J. and Omage, Z.E., 2022. The place of neglected and underutilized legumes in human nutrition and protein security in Nigeria. Critical Reviews in Food Science and Nutrition, 62(14), pp.3930-3938.
19. Ilić, A., Uhlarik, A. and Mamlić, Z., 2025. Drought Stress and Production of Legumes in Europe. In Marker-Assisted Breeding in Legumes for Drought Tolerance (pp. 77-105). Springer, Singapore.
20. Islam, M.A., Sarkar, D., Alam, M.R., Jahangir, M.M.R., Ali, M.O., Sarker, D., Hossain, M.F., Sarker, A., Gaber, A., Maitra, S. and Hossain, A., 2023. Legumes in conservation agriculture: A sustainable approach in rice-based ecology of the Eastern Indo-Gangetic Plain of South Asia– an overview. Technology in Agronomy, 3(1), pp.1-17.
21. Jena, J., Maitra, S., Hossain, A., Pramanick, B., Gitari, H.I., Praharaj, S., Shankar, T., Palai, J.B., Rathore, A., Mandal, T.K. and Jatav, H.S., 2022. Role of legumes in cropping system for soil ecosystem improvement. Ecosystem Services: Types, Management and Benefits. Nova Science Publishers, Inc, 415, pp.1-21.
22. Karavidas, I., Ntatsi, G., Vougeleka, V., Karkanis, A., Ntanasi, T., Saitanis, C., Agathokleous, E., Ropokis, A., Sabatino, L., Tran, F. and Iannetta, P.P., 2022. Agronomic practices to increase the yield and quality of common bean (Phaseolus vulgaris L.): A systematic review. Agronomy, 12(2), p.271.
23. Kebede, E., 2021. Contribution, utilization, and improvement of legumes-driven biological nitrogen fixation in agricultural systems. Frontiers in Sustainable Food Systems, 5, p.767998.
24. Khatun, M., Sarkar, S., Era, F.M., Islam, A.M., Anwar, M.P., Fahad, S., Datta, R. and Islam, A.A., 2021. Drought stress in grain legumes: Effects, tolerance mechanisms and management. Agronomy, 11(12), p.2374.
25. Kimani, E.N., Kamau, E.M. and Karimi, R., 2025. Crop Biodiversity: Utilization of Neglected and Underutilized Beneficial Legumes. In Legume Crops for Food Security-Cultivation and Benefits. IntechOpen.
26. Knez, M., Ranic, M., Gurinovic, M., Glibetic, M., Savic, J., Mattas, K. and Yercan, M., 2023. Causes and conditions for reduced cultivation and consumption of underutilized crops: is there a solution? Sustainability, 15(4), p.3076.
27. Kumar, R., Niwas, R., Khichar, M.L. and Leharwan, M., 2023. Assessment of sowing time and cultivars on growth, development and yield parameters of pigeonpea. Legume Research-An International Journal, 46(5), pp.604-608.
28. Kuyah, S., Sileshi, G.W., Nkurunziza, L., Chirinda, N., Ndayisaba, P.C., Dimobe, K. and Öborn, I., 2021. Innovative agronomic practices for sustainable intensification in sub-Saharan Africa. A review. Agronomy for Sustainable Development, 41, pp.1-21.

29. Lamichaney, A., Basavaraja, T., Katiyar, P.K. and Singh, N.P., 2021. Seed germination response of commonbean (Phaseolus vulgaris L.) genotypes to optimal and sub-optimal temperatures. Legume Research-An International Journal, 44(4), pp.419-424.
30. Lone, A.A., Khan, M.N., Gul, A., Dar, Z.A., Iqbal, A.M., Lone, B.A., Ahangar, A., Rasool, F.U., Ali, G. and Nisar, F., 2021. Common beans and abiotic stress challenges. Curr J Appl Sci Technol, 40(14), pp.41-53.
31. Mabhaudhi, T., Hlahla, S., Chimonyo, V.G.P., Henriksson, R., Chibarabada, T.P., Murugani, V.G., Groner, V.P., Tadele, Z., Sobratee, N., Slotow, R. and Modi, A.T., 2022. Diversity and diversification: ecosystem services derived from underutilized crops and their co-benefits for sustainable agricultural landscapes and resilient food systems in Africa. Frontiers in agronomy, 4, p.859223.
32. Mampholo, B., Mokgehle, S., Araya, N.A., Mofokeng, M., Makgato, M., Nyakane, N.E., Bairu, M., Truter, M., Mahlangu, R., Du Plooy, C.P. and Nciizah, A.D., 2024. Climate change resilient crops to Combat Food and Nutrition Insecurity in marginal lands. In The marginal soils of Africa: rethinking uses, Management and Reclamation (pp. 71-94). Cham: Springer Nature Switzerland.
33. Mansaray, A., Mark, Y.K., Moseray, M.T., Kamara, A.Y. and Conteh, A.R., 2020. Effect of cowpea cultivar, planting date and application of insecticide in the management of cowpea insect pests in South Eastern Sierra Leone. Journal of Entomology and Nematology, 12(2), pp.39-45
34. Matoso, A.O., Soratto, R.P., Guarnieri, F., Costa, N.R., Abrahão, R.C. and Tirabassi, L.H., 2018. Sowing date effects on cowpea cultivars as a second crop in Southeastern Brazil. Agronomy Journal, 110(5), pp.1799-1812.
35. Mofokeng, M.A., Bello, Z. and Mashingaidze, K., 2022. Phenotypic analysis of pigeon pea reveal genotypic variability under different environmental interaction. In Legumes Research-Volume 1. IntechOpen.
36. Obidiebube, E.A., Eruotor, P.G., Akparobi, S.O., Okolie, H. and Obasi, C.C., 2020. Assessment of Bambara Groundnut (*Vigna Subterranea* (L) Verdc) varieties for adaptation to rainforest agro-ecological zone of Anambra state of Nigeria. Crops, 5(1), pp.1-6.
37. Odeku, O.A., Ogunniyi, Q.A., Ogbole, O.O. and Fettke, J., 2024. Forgotten gems: exploring the untapped benefits of underutilized legumes in agriculture, nutrition, and environmental sustainability. Plants, 13(9), p.1208.
38. Popoola, J., Ojuederie, O. and Omonhinmin, C., 2020. Neglected and Underutilized Legume Crops: Improvement and. Recent advances in grain crops research, p.123.
39. Rasheed, A. and Azeem, F., 2024. Biofortification potential of neglected protein legumes for combating hidden hunger in resource-poor countries. In Biofortification of grain and vegetable crops (pp. 161-186). Academic Press.
40. Shah, F., Coulter, J.A., Ye, C. and Wu, W., 2020. Yield penalty due to delayed sowing of winter wheat and the mitigatory role of increased seeding rate. European Journal of Agronomy, 119, p.126120.
41. Sheoran, S., Ramtekey, V., Kumar, D., Kumar, S., Meena, R.S., Kumawat, A., Pradhan, G. and Shukla, U.N., 2022. Grain legumes: recent advances and technological interventions. Advances in legumes for sustainable intensification, pp.507-532.
42. Singh, G., Virk, H.K., Khokhar, A., Kaur, C., Brar, H.S., Singh, K., Singh, M., Kaur, K., Singh, M., Singh, M. and Kaur, G., 2023. Response of pigeon pea varieties to

sowing dates at high plant density under different agroclimatic zones of Punjab. Agricultural Research Journal, 60(1).

43. Sithole, N.J. and Magwaza, L.S., 2019. Long-term changes of soil chemical characteristics and maize yield in no-till conservation agriculture in a semi-arid environment of South Africa. Soil and Tillage Research, 194, p.104317.
44. Smith, M.R., Veneklaas, E., Polania, J., Rao, I.M., Beebe, S.E. and Merchant, A., 2019. Field drought conditions impact yield but not nutritional quality of the seed in common bean (Phaseolus vulgaris L.). PLoS One, 14(6), p.e0217099.
45. Suárez, J.C., Polanía, J.A., Contreras, A.T., Rodríguez, L., Machado, L., Ordoñez, C., Beebe, S. and Rao, I.M., 2020. Adaptation of common bean lines to high temperature conditions: Genotypic differences in phenological and agronomic performance. Euphytica, 216(2), p.28.
46. Suárez, J.C., Polanía, J.A., Contreras, A.T., Rodríguez, L., Machado, L., Ordoñez, C., Beebe, S. and Rao, I.M., 2020. Adaptation of common bean lines to high temperature conditions: Genotypic differences in phenological and agronomic performance. Euphytica, 216(2), p.28.
47. Vilakazi, B., Mafongoya, P.L., Odindo, A.O. and Phophi, M.M., 2025. The role of neglected grain legumes in Food and Nutrition Security and Human Health. Sustainability, 17(1), p.350.
48. Vilakazi, B., Odindo, A.O., Phophi, M.M. and Mafongoya, P.L., 2025. Socioeconomic Factors Influencing Crop Diversification Among Smallholder Farmers in Bergville, South Africa. Agriculture, 15(9), p.914.
49. Wani, A.B., Biaza and Irtiza, 2021. Neglected and underutilized crops: present status and future prospectus. Neglected and Underutilized Crops-Towards Nutritional Security and Sustainability, pp.51-70.
50. Zafar, T., Mehra, A., Das, P., Shaik, B. and Malik, A.A., 2024. Demystifying the advanced interventions of genetics and modern breeding approaches for nutritional security and sustainability of neglected and underused crop species (NUCS). Genetic Resources and Crop Evolution, 71(2), pp.559-577.

Chapter 6: Cropping Systems Effect on the Adaptability of Neglected Legumes in Rainfed Conditions

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Abstract

Cropping systems are critical in modifying micro-environments, improving land-use efficiency, and enhancing crop adaptability to marginal conditions. However, the interaction between cropping systems and the performance of neglected legumes under rainfed conditions remains poorly understood. This study evaluated the effects of cropping systems on the adaptability of neglected legumes in rainfed environments. Field trials were conducted over two consecutive summer growing seasons (2022/23 and 2023/24) using a split-plot randomized complete block design with three replications. Phenological traits (emergence, flowering, podding, and senescence), yield components (pods per plant, seeds per pod, pod mass, 100-seed weight and grain yield (t ha^{-1})), and land equivalent ratio (LER) was recorded and analyzed using GenStat® and principal component analysis. Significant effects of cropping system, cultivar, season, and their two- and three-way interactions ($P \leq 0.05$) were observed for all measured traits, confirming that legume-based intercropping systems significantly influence the adaptability and productivity of neglected legumes under rainfed conditions. Intercropping enhanced early emergence and accelerated reproductive development in legumes such as Bambara groundnut, cowpea, and common bean, while pigeon pea showed reduced establishment under sole cropping due to competitive suppression. Pod production, pod mass, and grain yield consistently increased under intercropping. Cowpea and Bambara groundnut exhibited stable responses across seasons, whereas common bean and pigeon pea showed greater variability, highlighting the importance of genotype and species-specific compatibility with intercrop designs. LER consistently exceeded 1.0 under intercropping, confirming the superior land-use efficiency and yield potential of intercropping in smallholder agroecosystems. These findings underscore the importance of strategic selection of legume species with complementary phenology, growth dynamics, and resource requirements to optimize interspecific interactions and enhance system productivity.

Keywords: Rainfed agriculture, crop adaptability, agroecological zones, intercropping, resource use efficiency, agronomic performance, land equivalent ratio

6.1 Introduction

Neglected legumes possess significant untapped potential to enhance food security, improve soil fertility, and strengthen climate change resilience in sub-Saharan Africa (Ayilara et al., 2022; Odeku et al., 2024). These legumes are well-adapted to low-input, marginal environments and often outperform major crops in drought-prone or nutrient-deficient soils (Chandra et al., 2020; Icka and Damo, 2023). Their ability to fix atmospheric nitrogen, thrive under erratic rainfall conditions, and provide high-quality protein and micronutrients makes them particularly relevant for smallholder farmers operating in rainfed agroecosystems (Popoola et al., 2020; Naresh et al., 2025; Vilakazi et al., 2025). Moreover, their roles in dietary diversification and income generation are increasingly recognized as critical to improving rural livelihoods and achieving Sustainable Development Goals (SDGs), especially those related to zero hunger and climate action (Li et al., 2020). Despite these agronomic and nutritional advantages, neglected legumes remain significantly underutilized in both research and development agendas due to limited breeding efforts, inadequate extension services, poor seed system infrastructure, and weak market linkages (Rokka et al., 2025; Templer et al., 2025). As a result, their production is often relegated to subsistence or intercrop niches with minimal external support (Adelabu and Franke, 2023). These challenges are further amplified under rainfed conditions, which dominate much of the African agricultural landscape and are increasingly vulnerable to climate variability and extreme weather events.

The production and adaptability of neglected legumes are often constrained by several factors, including erratic rainfall, low soil fertility, and limited access to improved varieties or agronomic practices (Abobatta et al., 2021; Abobatta et al., 2022). Monoculture or sole cropping systems frequently exacerbate these challenges, as they fail to optimize resource use or buffer against environmental stress (Mukhovi and Jacobi, 2022). However, cropping systems, especially intercropping, crop rotation, and relay cropping, are proven agroecological approaches for enhancing resource use efficiency, improving soil structure and fertility, and reducing biotic and abiotic stresses (Ayilara et al., 2022; Baker et al., 2023). According to Mihrete and Mihretu (2025), these systems can influence the adaptability of crops by altering the microclimate, enhancing soil moisture retention, and optimizing temporal and spatial resource distribution. For neglected legumes, these practices may help overcome some of the environmental constraints by limiting their productivity and establishing them as reliable components of diversified farming systems (Maitra et al., 2025). However, the majority of cropping system research has traditionally focused on staple cereals and high-input legumes, leaving a significant knowledge gap regarding how various systems affect the adaptability and yield stability of neglected legumes in low-input, rainfed environments. Their influence on the performance and adaptability of neglected legumes remains poorly understood, especially under field conditions in marginal areas. Given the pressing need to diversify cropping portfolios in South African smallholder agriculture, it is essential to evaluate how these systems influence the establishment, phenological development, and yield under local agroecological conditions.

Although extensive research has been conducted on major legumes and cereals under high-input production systems (Popoola et al., 2020), there remains a critical knowledge gap regarding the influence of cropping systems on the performance and adaptability of neglected legumes in rainfed environments. This gap underscores efforts to mainstream these crops into sustainable farming systems, particularly in regions where they could offer climate resilience and livelihood benefits. As a result, addressing this gap requires a holistic understanding of the interactions between cropping systems, neglected legumes, and agroecological performance. In this context, evaluating the adaptability of neglected legumes under different cropping systems is essential to realizing their full potential in sustainable agriculture and rural development. This study investigates the effects of selected cropping systems, namely intercropping and sole cropping systems, on the adaptability of Bambara groundnut, cowpea, pigeon pea, and common bean under rainfed conditions. The primary objective is to identify agronomic practices that enhance the productivity, resource-use efficiency, and environmental resilience of these legumes when grown in water-limited environments. Specific focus is on crop growth parameters, yield performance, and the land equivalent ratio within cropping systems. The findings from this research are expected to contribute to the body of knowledge supporting sustainable intensification in sub-Saharan Africa by promoting the integration of climate-resilient, neglected legumes into diverse cropping systems. Additionally, the findings will inform policy interventions, extension services, and farmer decision-making frameworks aimed at enhancing agrobiodiversity, climate adaptation, and the resilience of smallholder rainfed agriculture.

6.2 Materials and Methods

6.2.1 Description of the Study Area

Field experiments were conducted over two consecutive summer growing seasons (2022/2023 and 2023/2024) in Bergville, a rainfed agroecological zone in KwaZulu-Natal, South Africa. The first season (2022/2023) was conducted at Site 1, and the second season (2023/2024) at Site 2, representing two sites within the study area. These sites were selected for their ecological heterogeneity and agricultural relevance. Bergville is situated at approximately 28°43′49.74″S and 29°21′4.20″E, at an elevation ranging from 1,200 to 1,800 meters above sea level. The region receives an average annual rainfall between 700 mm and 1,200 mm (Mthembu and Mkhize, 2025). Winter minimum temperatures range from 2°C to 5°C, with occasional frost events, while summer maximum temperatures (December to February) range between 25°C and 30°C (Vilakazi et al., 2025). This climatic variability, characterized by semi-arid conditions and pronounced seasonal fluctuations in rainfall and temperature, renders the area suitable for investigating the interactions between agricultural practices and ecological dynamics, particularly in relation to smallholder farming systems and biodiversity. Water sources in the region primarily consist of constructed pits, earth dams, and rainwater harvesting systems, with most smallholder farmers relying on rainfall for crop irrigation (Vilakazi et al., 2025).

6.2.2 Experimental design and layout

The experiment was established using a split-plot arrangement within a randomized complete block design (RCBD) to facilitate efficient management of harvesting and data collection across varying cropping systems. The main plot factor was the cropping system, comprising two levels: (i) sole cropping (monoculture of each legume species) and (ii) intercropping with maize. The subplot factor was legume species, including four medium duration species: Bambara groundnut (*Vigna subterranea*), cowpea (*Vigna unguiculata*), pigeon pea (*Cajanus cajan*), and common bean (*Phaseolus vulgaris*). Each main plot (cropping system) was divided into subplots corresponding to the individual legume species. The experiment included three replications for each cropping system and legume species. Each experimental plot measured 4 m × 4 m (16 m^2). Land preparation was carried out using a disc plough. Sowing was performed manually at the onset of the summer season (November) using a hand dibber to a depth of 5 cm. Plant spacing varied among the legume species as follows: common bean (15 cm × 40 cm), Bambara groundnut (10 cm × 50 cm), pigeon pea (30 cm × 60 cm), and cowpea (30 cm × 60 cm). Two seeds were sown per hill and subsequently thinned to one seedling per stand 15 days after emergence. Crop establishment methods were tailored to species-specific agronomic requirements. Pigeon pea, cowpea, and common bean were planted in furrows, while Bambara groundnut was sown on mounded ridges, which were constructed four weeks after sowing. All plots were managed under rainfed conditions without supplemental irrigation to simulate typical smallholder farming systems. No chemical fertilizers or soil amendments were applied during the trial period. Weed control was conducted manually at regular intervals. To manage pest pressure, all plots were treated with Karate® (lambda-cyhalothrin) insecticide targeting stink bugs (*Chinavia hilaris and Euschistus servus*), beetles (*Coleoptera spp*), and aphids (*Aphididae spp*).

6.2.3 Data collection

6.2.3.1 Climate data

Table 6.1: Rainfall and temperature distribution during the 2022/2023 and 2023/2024 growing seasons (October–January) in Bergville, KwaZulu-Natal, South Africa.

	Rainfall (mm/month)		**Min Temperature (°C)**		**Max Temperature (°C)**	
Month	**S1**	**S2**	**S1**	**S2**	**S1**	**S2**
October	148	115	11,4	11	25,5	26
November	196	104	13,6	12	26,7	26
December	295	200	15,2	14	28,3	27
January	291	312	16,2	14,9	29,3	25,5

Note that S1 indicates Season 1(2022/23), S2; Season 2 (2223/24)

Table 6.1 represents the meteorological data, including rainfall and temperature, obtained from the accessible website https://www.weather2visit.com/africa/south-africa/bergville.htm, which provides comprehensive climatic information for Bergville, KwaZulu-Natal, South Africa. Analysis of weather conditions during the 2022/2023 and 2023/2024 growing seasons (October to January) revealed interannual variability in both temperature and precipitation. During the 2022/2023 season, an increase in temperature was observed, with minimum temperatures rising from 11.4 °C in October to 16.2 °C in January, and maximum temperatures ranging from 25.5 °C to 29.3 °C. In contrast, the 2023/2024 season was characterized by slightly cooler conditions, with minimum temperatures ranging from 11.0 °C to 14.9 °C. Maximum temperatures exhibited a more constrained range, peaking at 27.0 °C in December before declining to 25.5 °C in January. Rainfall patterns also differed substantially between seasons. The cumulative precipitation for October to December was significantly lower in 2023/2024 compared to 2022/2023. Monthly rainfall totals for October, November, and December 2023/2024 were 115 mm, 104 mm, and 200 mm, respectively, representing declines of 22%, 47%, and 32% relative to the corresponding months in the previous season. However, January 2024 received 312 mm of rainfall, slightly exceeding the 291 mm recorded in January 2023. These interannual differences indicate a relatively cooler and drier environment during the early stages of the 2023/2024 growing season.

6.2.3.2 Soil properties and chemical analysis

Prior to the establishment of field trials, soil samples were collected from a 0-20 cm depth at both experimental sites to assess initial soil physicochemical properties. The samples were submitted to the Cedara Agricultural Laboratory in Pietermaritzburg, South Africa, for analysis, as outlined in chapter 5.

6.2.3.3 Phenological traits

Phenological data were collected from the inner two rows of each plot to minimize boarder effects. Emergence was monitored daily for two weeks following sowing through visual assessment. Emergence was considered complete when no new seedlings appeared for three consecutive days and at least 90% of the final crop stand had emerged.

Phenological development was recorded in terms of days to flowering, days to podding, and days to leaf senescence. Each phenological stage was recorded when at least 50% of the plants within a plot had reached the respective stage. Days to podding were defined as the number of days from sowing to the appearance of the first pods on 50% of the plants. Days to leaf senescence were recorded as the number of days from sowing until at least 50% of the leaves had turned yellow or brown, with no subsequent leaf regeneration.

6.2.3.4 Yield Component Measurement and Land Use Efficiency

At physiological maturity, five representative plants were randomly selected from the inner two rows of each plot for yield component assessment. The measured parameters included the number of pods per plant, the number of seeds per pod, pod mass, and 100-seed weight. These components were used to evaluate seed yield responses across cropping systems. The number of pods per plant was determined by manually counting all fully developed pods on each sampled plant. After harvest, the pods were air-dried and weighed using a digital precision balance (±0.01 g accuracy) to determine pod mass. The dried pods were then manually threshed, and the number of seeds per pod was recorded by counting all seeds from each plant. The 100-seed weight was obtained by randomly selecting and weighing 100 seeds using the same precision balance.

6.2.3.5 Grain yield determination

Grain yield was determined for cowpea, common bean, pigeon pea, and Bambara groundnut based on harvested grain from a defined net plot area. At physiological maturity, plants from the central rows of each plot, excluding border rows, were manually harvested. The harvested material was sun-dried to a constant weight, threshed manually, and grains were weighed. Yields were then expressed in tons per hectare (t ha^{-1}), adjusted to standard moisture content.

This method follows standard procedures described by Gomez and Gomez (1984) and is widely used in legume field trials under rainfed conditions.

6.2.3.6 Land Equivalent Ratio (LER)

For intercropping treatments, land use efficiency was assessed using the Land Equivalent Ratio (LER), which quantifies the relative land area required under sole cropping to produce the equivalent yield obtained in intercropping. The land equivalent ratio (LER) for the maize-legume intercropping system was calculated using Equation 2, as defined by Hirpa (2014).

$$\mathrm{LER} = \frac{Mym}{Mys} + \frac{Lym}{Lys} \qquad (1)$$

Where:

M_{ym} = maize yield in the mixture

M_{ys} = maize yield in sole

L_{ym} = legume yield in mixture

L_{ys} = legume yield in sole

6.2.3.7 Data analysis

Data from the two growing seasons (2022/2023 and 2023/2024) were analyzed using analysis of variance (ANOVA) in GenStat® statistical software (14th edition). Treatment means were compared using the least significant difference (LSD) test at a 5% significance level ($P < 0.05$). Multivariate statistical techniques, including principal component analysis (PCA) and correlation analysis, were performed to identify patterns and explore relationships among the measured variables.

6.3 Results

6.3.1 Effect of Cropping System on Key Phenological Stages of Legume Species

The results revealed significant effects of season on emergence and senescence ($P < 0.05$), as well as highly significant interactions between season and legume species for all phenological stages, including days to 50% flowering and podding. Interactions between species and cropping system were also highly significant ($P < 0.05$) for flowering, podding, and senescence. Significant three-way interactions were observed for both emergence and senescence (Table 6.2). Emergence differed significantly ($P < 0.05$) among legume crops and cropping systems. Intercropping improved emergence, particularly for Bambara groundnut and cowpea in the second season, where increases of 9.8% and 12%, respectively, were observed compared to sole cropping. Common bean also showed higher emergence under intercropping, with values increasing from 69.8% to 79.7% in the second season. In contrast, pigeon pea showed reduced emergence under both cropping systems in the second season, declining to 68.1% under sole cropping. Phenological development also varied among legume crops and cropping systems. Pigeon pea exhibited the longest durations to flowering, podding, and senescence across all treatments. However, intercropping significantly accelerated its development, reducing days to flowering and podding by approximately 51 and 50 days, respectively, in the first season. This trend was also observed in the second season. Common bean and cowpea flowered and podded earlier than the other species. In common bean, flowering occurred at 43.3 and 41 days under sole cropping in the first and second seasons, respectively, and was reduced to 38.3 and 37.8 days under intercropping. Similarly, days to podding were shortened from 60.7 and 63.6 days under sole cropping to 48.5 and 51.2 days under intercropping. Cowpea also showed earlier flowering and podding under intercropping, with flowering reduced by approximately 15 days in the first season (from 59.9 to 45.2 days) and by 18 days in the second season (from 57.5 to 39.58 days). Bambara groundnut demonstrated consistent phenological development across seasons and cropping systems, with flowering ranging from 48.1 to 51.2 days and podding from 68.1 to 70.2 days.

Table 6.2: Effect of cropping system on key phenological stages of legume species. 90% Emer; 90% emergence; D50%F = days to 50% flowering; D50%P = days to 50% podding; DS = days to Senescence.

		90% Emer		**D50%F**		**D50%P**		**D50%S**	
Legume Species (LS)	**Cropping system (CS)**	**S1**	**S2**	**S1**	**S2**	**S1**	**S2**	**S1**	**S2**
Common bean	1	78.4	69.8	43,3	41,2	60,7	63,6	91,9	93,0
	2	83,6	79,7	38,3	37,8	48,5	51,2	76,3	76,9
Pigeon pea	1	84,2	68.1	157,1	169,5	190,3	194,5	245,9	258,9
	2	88,2	73,2	106,1	120,8	140,3	151,9	188,4	198,0
Cowpea	1	75,2	78.4	59,9	57,5	80,1	79,4	109,2	110,4
	2	78,3	90,4	45,2	39,6	62,4	59,6	90,6	88,9
Bambara groundnut	1	81,3	75.3	50,2	51,2	68,4	68,1	123,6	124,8
	2	90,3	85,2	48,1	48,7	70,2	69,9	115,6	122,3
F test	-	*		NS		NS		*	
LSD 5%	-	3.88		2.442		1.879		3.435	
Interaction									
S x LS		**		***		***		***	
S x CS		NS		NS		NS		NS	
LS x CS		*		***		***		***	
S x LS x CS		*		NS		NS		*	

Note that *, **, *** and NS indicate P < 0.05, <0.01, <0,001 and not significant, respectively. Cropping systems 1 & 2 = Sole cropping and intercropping; Season 1 & 2 = 2022/23 &2023/24, respectively

6.3.2 *Effect of Cropping System on the Number of Pods per Plant*

Highly significant differences ($P < 0.05$) were observed among legume species and between cropping systems for the number of pods per plant. Interactions between species and cropping system were also highly significant ($P< 0.05$). A significant three-way interaction was observed ($P < 0.05$), as illustrated in Figure 6.1. Across all legumes and growing seasons, the number of pods per plant was consistently higher under intercropping than under sole cropping. In the 2022/23 season, pigeon pea showed the highest number of pods per plant, increasing from 23.1 under sole cropping to 29.9 under intercropping. Cowpea and Bambara groundnut increased under intercropping, with cowpea rising from 15.58 to 20.54 and Bambara groundnut from 9.1 to 15.79 pods per plant. Common bean followed a similar trend, increasing from 5.17 to 7.38 pods per plant under intercropping. A similar trend was observed in the 2023/24 season, where cowpea recorded the highest number of pods per plant under intercropping (28.38), followed by pigeon pea (25.08). Bambara groundnut exhibited the greatest improvement in pod number under sole cropping between seasons, increasing from 9.1 to 20.56 pods per plant.

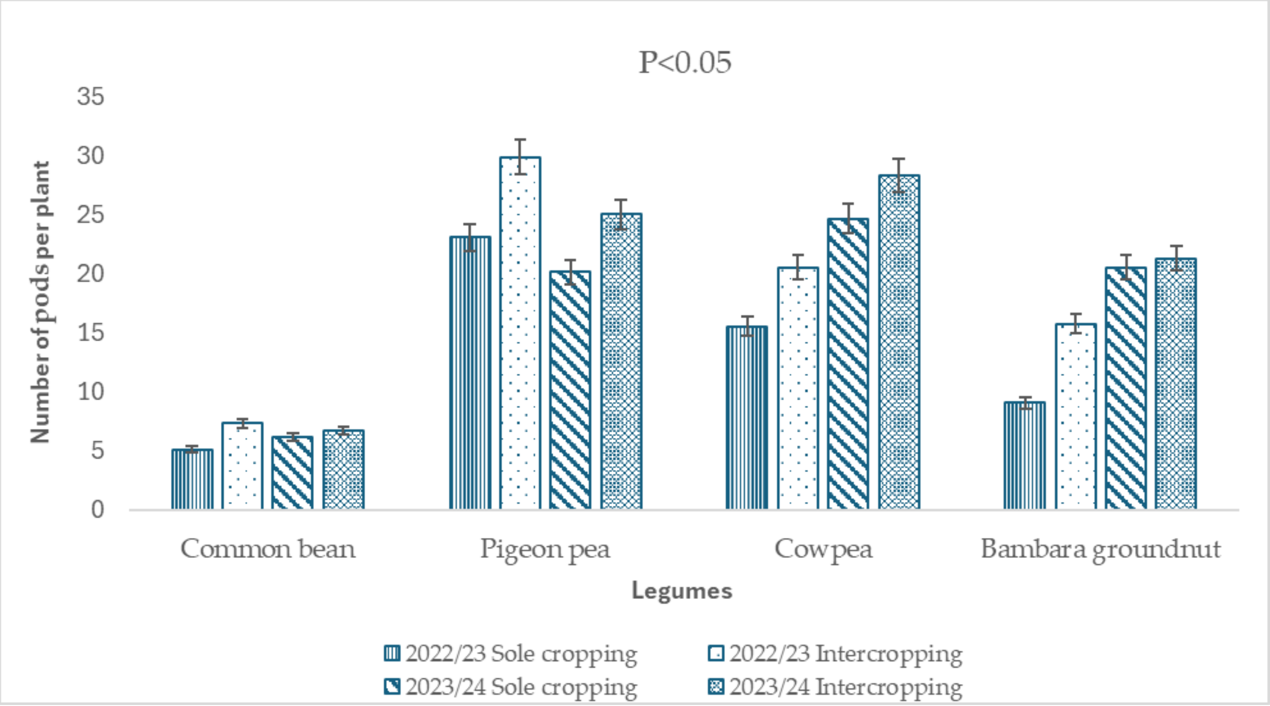


Figure 6.1: Effect of cropping system on the number of pods per plant in four legume species during the 2022/23 and 2023/24 growing seasons.

6.3.3 *Effect of Cropping System on Pod Mass*

Pod mass was significantly influenced by both legume species and cropping system ($P < 0.05$). Interactions for pod mass were not significant ($P > 0.05$). Intercropping enhanced performance across both seasons (Figures 6.2). In the 2022/23 season, all four legume crops showed increased pod mass under intercropping compared to sole cropping. Cowpea recorded the highest pod mass, increasing from 2.67 g under sole cropping to 3.17 g under intercropping. Common bean and Bambara groundnut also improved, rising from 1.68 g to 2.10 g and from 1.10 g to 1.21 g, respectively. Pigeon pea exhibited an increase from 0.46 g to 0.99 g per pod under intercropping. This positive response to intercropping was also observed in the 2023/24 season, particularly for pigeon pea and common bean. Pigeon pea pod mass increased from 0.38 g under sole cropping to 2.71 g under intercropping, while common bean rose from 1.22 g to 1.93 g. Cowpea pod mass also increased from 1.35 g to 2.23 g. In contrast, Bambara groundnut demonstrated minimal variation across seasons and cropping systems, with pod mass remaining relatively stable (1.10-1.21 g).

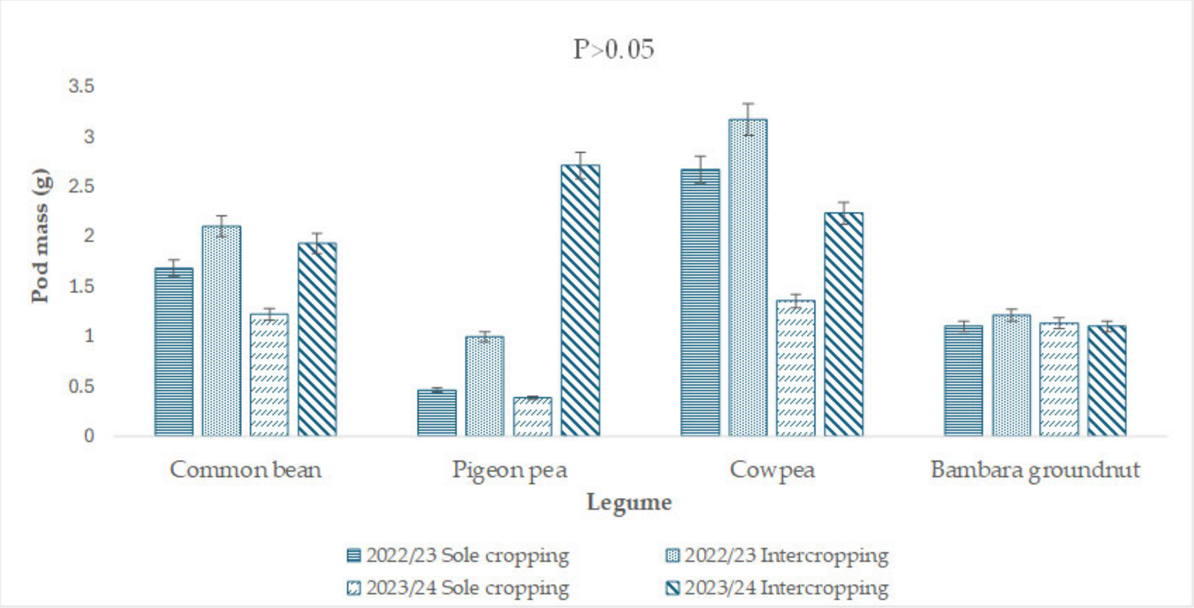


Figure 6.2: Effect of cropping system on pod mass in four legume crops across two growing seasons (2022/23 and 2023/24).

6.3.4 Effect of Cropping System on Land Equivalent Ratio in Four Legume Species

Land equivalent ratio (LER) was significantly affected by legume species and cropping system ($P < 0.05$). LER values consistently demonstrated the advantage of intercropping across all four legume species and both growing seasons (Figure 6.3). In the 2022/23 and 2023/24 seasons, LER values under intercropping consistently exceeded 1.0 for all legumes. In 2022/23, cowpea showed the highest LER under intercropping (1.62), followed by Bambara groundnut (1.56), pigeon pea (1.48), and common bean (1.36).

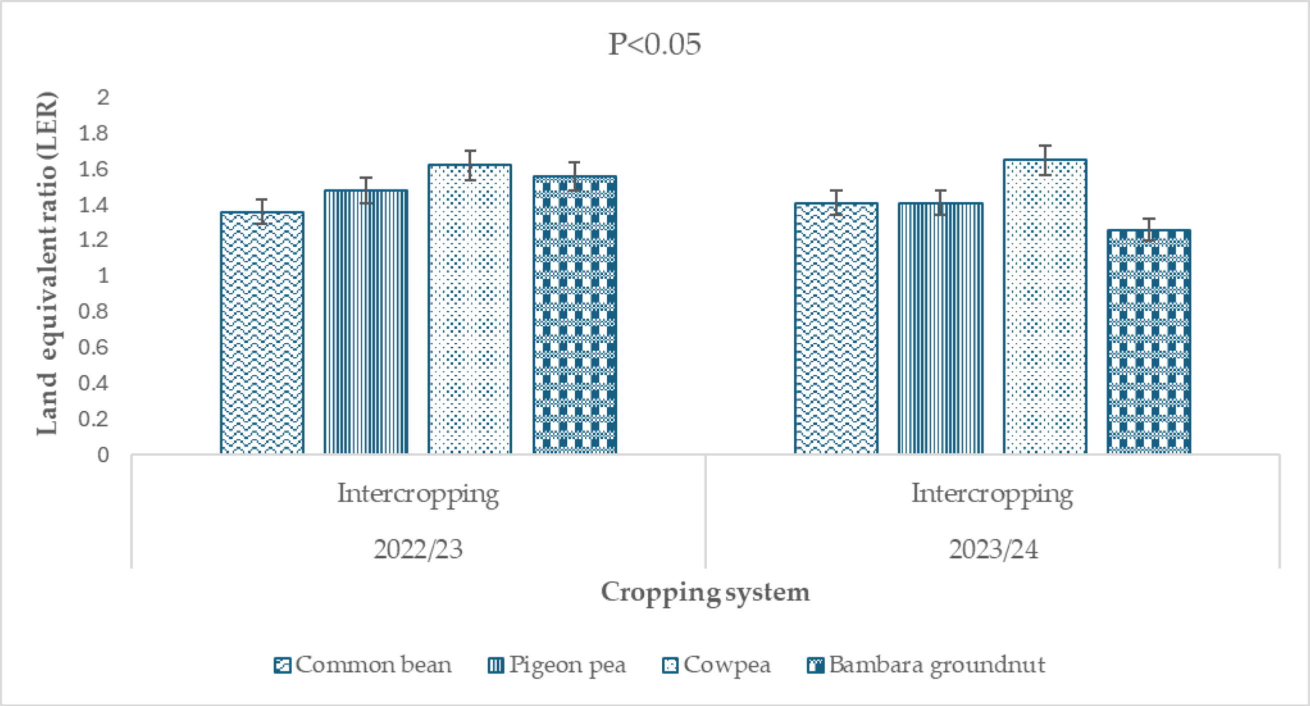


Figure 6.3: Effect of cropping system on land equivalent ratio in four legume species across two growing seasons (2022/23 and 2023/24).

6.3.5 Effect of Cropping System on Grain Yield of Four Legumes Species

Table 6.3 illustrates a consistent grain yield (t ha^{-1}) advantage under intercropping across all legume species and seasons, with significant variation among species ($P < 0.05$). Cowpea showed the highest yield advantage under intercropping, with yields increasing from 1.42 t ha^{-1} under sole cropping to 1.84 t ha^{-1} and 1.98 t ha^{-1} under intercropping in the 2022/23 and 2023/24 seasons, respectively. Similarly, common bean and Bambara groundnut exhibited notable yield gains in both seasons. For common bean, intercropping increased yields from 0.98 to 1.25 t ha^{-1} in 2022/23 and 1.26 to 1.73 t ha^{-1} in 2023/24. Bambara groundnut also responded positively, with intercropping improving yields by more than 0.3 t ha^{-1} in both seasons. Pigeon pea demonstrated modest but consistent yield improvements, with increases of 0.24 t ha^{-1} in 2022/23 and 0.23 t ha^{-1} in 2023/24 under intercropping compared to sole cropping.

Table 6.3: Effect of cropping system on grain yield of four legume species across two growing seasons (2022/23 and 2023/24).

		Yield (t/ha)	
Legume Specie (LS)	**Cropping Systems (CS)**	**Season 1**	**Season 2**
Common bean	Sole cropping	0,98	1,26
	Intercropping	1,25	1,73
Pigeon pea	Sole cropping	1,10	1,02
	Intercropping	1,34	1,25
Cowpea	Sole cropping	1,42	1,51
	Intercropping	1,84	1,98
Bambara groundnut	Sole cropping	1,02	1,18
	Intercropping	1,35	1,41
F test	-	*	
LSD 5%	-	0.520	

Note that * indicate $P < 0.05$. Season 1 & 2 = 2022/23 &2023/24

6.3.6 Principal Component Analysis (PCA) for Assessed Traits

Table 6.4 shows the PCA with factor loadings, eigenvalues, and percentage variance for the evaluated traits evaluated under sole cropping and intercropping systems. Under sole cropping, the first three principal components (PC1, PC2, and PC3) collectively accounted for 100% of the total variation, with PC1 accounting for the highest proportion (56.25%). PC1 was correlated with phenological traits, including days to flowering (DF: 0.434), days to podding (DP: 0.431), and days to senescence (DS: 0.443), suggesting that these traits were the primary contributors to variability under sole cropping. In contrast, pod mass (PM), seed weight (SW), and land equivalent ratio (LER) showed negative correlation with PC1. Under intercropping, the first three principal components similarly explained 100% of the total variation, with PC1, PC2, and PC3 accounting for 45.92%, 35.82%, and 18.26% of the variance, respectively. As in sole cropping, PC1 was correlated with phenological traits with lower loading coefficients. Yield component traits such as PM, number of seeds per pod (NSP), and LER correlated with PC2, indicating a shift in trait influence under intercropping. PC3, under both cropping systems, represented a variation, with contributions from emergence (EM) and number of pods per plant (NPP). The PCA showed phenological traits as dominant sources of variation across both cropping systems. However, intercropping modified trait contributions by enhancing the relative influence of productivity and resource-use efficiency traits (PM, NSP, LER). These results suggest that intercropping not only affects developmental dynamics but also broadens the trait spectrum contributing to yield, reinforcing its advantages in terms of land-use efficiency and agronomic performance.

Figure 6.4 presents the PCA biplots of PC1 versus PC2, illustrating the associations among assessed traits and four legume crops under sole cropping and intercropping systems. Under sole cropping, PC1 was correlated with phenological traits such as days to flowering, podding, and senescence, suggesting that growth duration was the main source of variability among legume crops. Common bean and pigeon pea were grouped along PC1, indicating similar phenological development. Bambara groundnut, which matured earlier, aligned more distantly, reflecting shorter phenological durations. In contrast, under intercropping, PC2 was correlated with yield-related traits, including pod mass (PM), number of seeds per pod (NSP), and land equivalent ratio (LER). Cowpea and Bambara groundnut were grouped along PC2, reflecting their enhanced performance in terms of seed productivity and land-use efficiency under intercropping. The separation of species in the biplot highlights how intercropping altered trait contributions and differentiated legume responses, particularly by enhancing productivity traits in cowpea and Bambara groundnut. The PCA demonstrates that while phenological traits dominated variability under sole cropping, intercropping introduced greater influence from yield and efficiency traits. This shift underscores the role of intercropping in enhancing the functional diversity and performance of legume species within mixed cropping systems.

Table 6.4: Summary of factor loadings, eigenvalue, percent and cumulative variation for assessed traits under sole cropping and intercropping.

	Sole cropping			**Intercropping**		
Traits	**PC 1**	**PC2**	**PC3**	**PC1**	**PC 2**	**PC3**
EM	0,056	-0,248	0,728	-0,308	-0,057	0,602
DF	0,434	0,138	-0,048	0,434	-0,262	-0,009
DP	0,431	0,150	-0,058	0,431	-0,265	0,047
DS	0,443	0,047	-0,011	0,391	-0,324	0,130
NPP	0,282	0,238	0,542	0,378	0,024	0,499
NSP	-0,123	0,585	0,272	0,175	0,517	0,084
PM	-0,391	0,264	0,198	0,155	0,519	-0,137
SW	-0,192	-0,555	0,236	-0,386	-0,222	0,370
LER	-0,377	0,344	-0,037	0,175	0,407	0,454
Eigenvalue	5,062	2,354	1,583	4,133	3,224	1,643
Variance (%)	56,252	26,157	17,591	45,922	35,820	18,258
Cumulative (%)	56,252	82,409	100	45,922	81,742	100

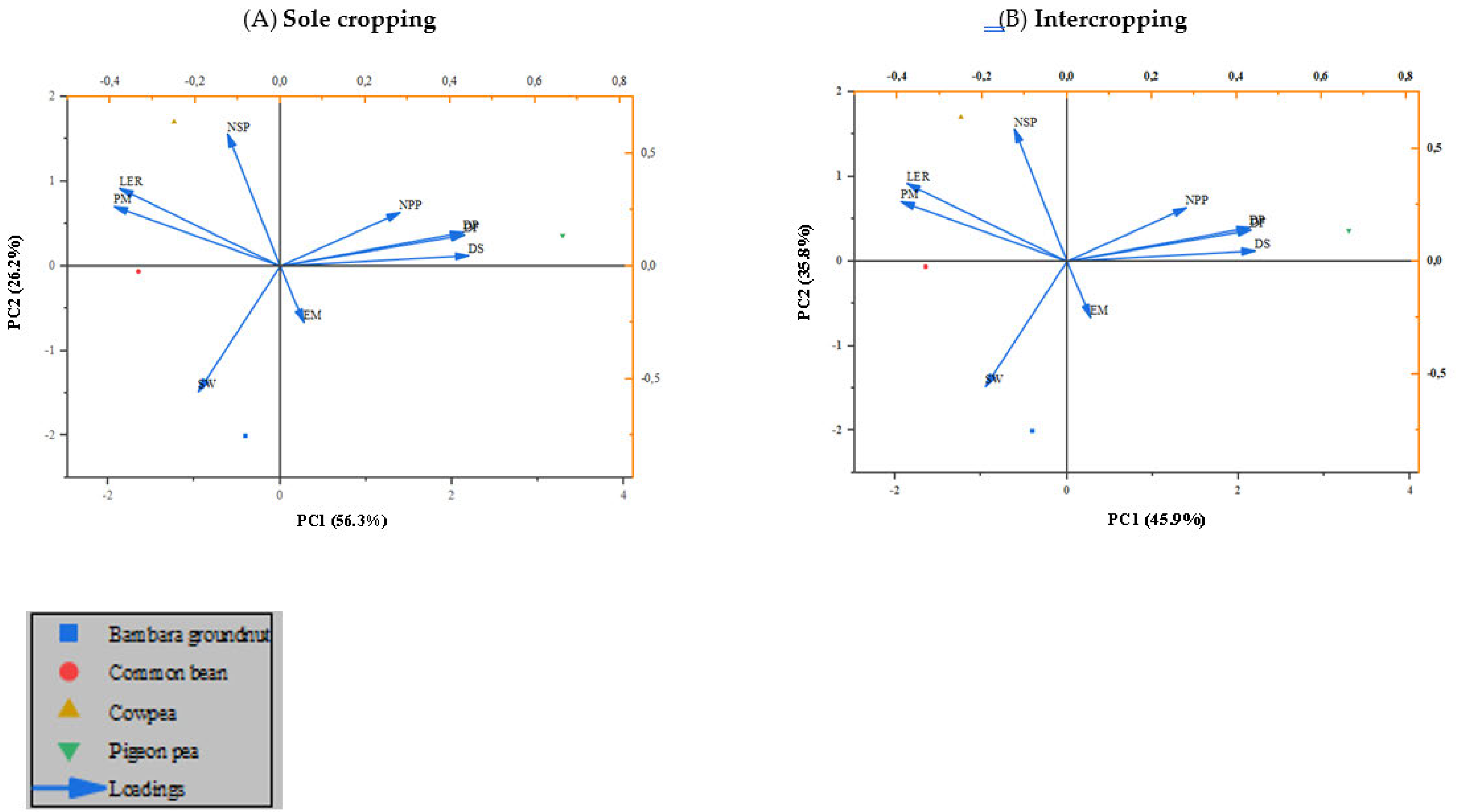
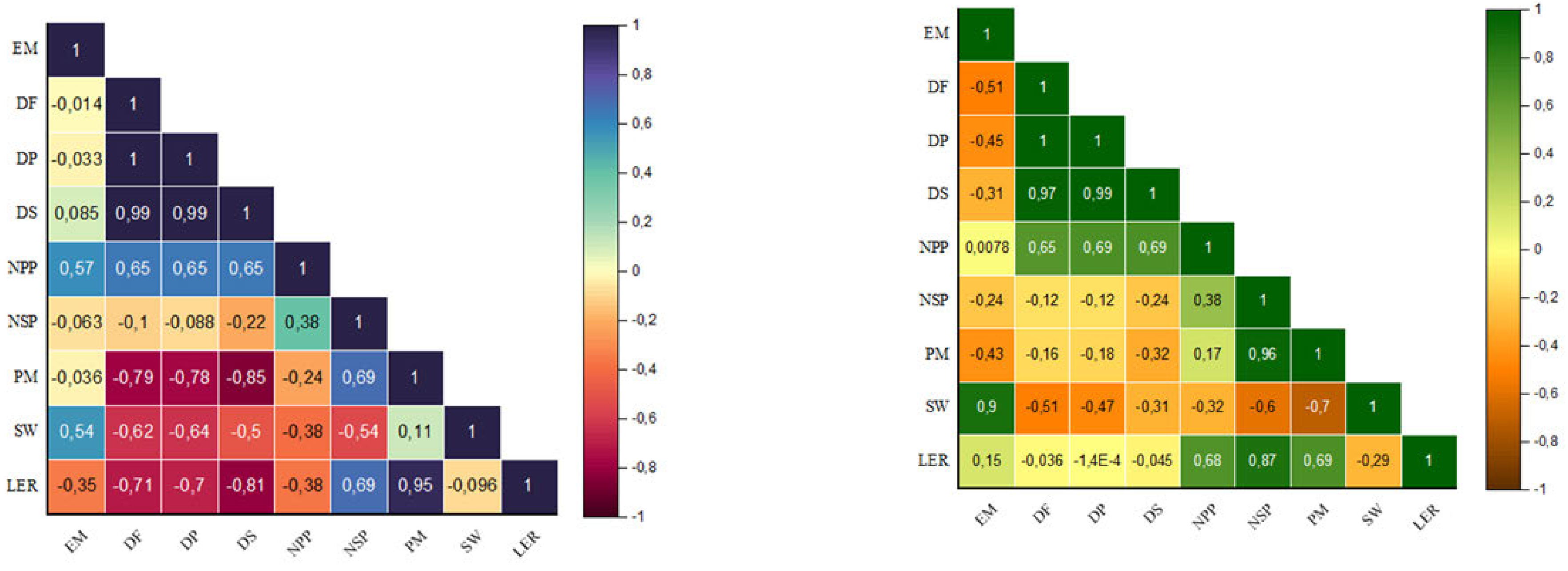


Figure 6.4: Principal Component (PC) biplots of PC1 vs PC2 illustrating the relationships between assessed traits and legume species under sole cropping and intercropping

6.3.7 Correlation Analysis for Assessed Traits

Figure 6.5A and 6.5B present correlation analyses illustrating the relationships among assessed traits under sole cropping and intercropping systems. Under sole cropping (Figure 6.5A), days to senescence were positively correlated with emergence, days to flowering (r = 0.99) and days to podding (r = 0.99). The number of pods per plant also showed positive correlations with phenological traits, including emergence (r = 0.57), days to flowering (r = 0.65), podding (r = 0.65), and senescence (r = 0.65). A positive association was observed between the number of seeds per pod and the number of pods per plant (r = 0.38). Pod mass was positively correlated with the number of seeds per pod (r = 0.69), and seed weight positively correlated with pod mass (r = 0.11). Land equivalent ratio (LER) exhibited strong positive correlations with both pod mass (r = 0.69) and seed weight (r = 0.95), suggesting that yield components were closely linked to land-use efficiency. Under intercropping (Figure 6.5B), days to senescence remained positively correlated with days to flowering (r = 0.97) and days to podding (r = 0.99) but negatively correlated with emergence (r = –0.31), indicating a shift in trait interactions under mixed cropping. The number of pods per plant maintained positive correlations with phenological traits, including emergence, days to flowering (r = 0.65), and both podding and senescence (r = 0.69). Similarly, the number of seeds per pod was again positively associated with the number of pods per plant (r = 0.38). Pod mass was correlated with the number of seeds per pod (r = 0.96) and showed a weaker association with the number of pods per plant (r = 0.17). Seed weight positively correlated with emergence (r = 0.90). LER demonstrated moderate to strong positive correlations with the number of pods per plant (r = 0.68), number of seeds per pod (r = 0.87), and pod mass (r = 0.69), emphasizing the influence of yield traits on intercropping advantage. These correlations highlight consistent trait interactions across systems, with intercropping enhancing associations between yield components and land-use efficiency, thus reinforcing the agronomic benefits of mixed cropping strategies.



	EM	DF	DP	DS	NPP	NSP	PM	SW	LER
EM	1								
DF	-0,014	1							
DP	-0,033	1	1						
DS	0,085	0,99	0,99	1					
NPP	0,57	0,65	0,65	0,65	1				
NSP	-0,063	-0,1	-0,088	-0,22	0,38	1			
PM	-0,036	-0,79	-0,78	-0,85	-0,24	0,69	1		
SW	0,54	-0,62	-0,64	-0,5	-0,38	-0,54	0,11	1	
LER	-0,35	-0,71	-0,7	-0,81	-0,38	0,69	0,95	-0,096	1

(A) **Sole cropping**

	EM	DF	DP	DS	NPP	NSP	PM	SW	LER
EM	1								
DF	-0,51	1							
DP	-0,45	1	1						
DS	-0,31	0,97	0,99	1					
NPP	0,0078	0,65	0,69	0,69	1				
NSP	-0,24	-0,12	-0,12	-0,24	0,38	1			
PM	-0,43	-0,16	-0,18	-0,32	0,17	0,96	1		
SW	0,9	-0,51	-0,47	-0,31	-0,32	-0,6	-0,7	1	
LER	0,15	-0,036	-1,4E-4	-0,045	0,68	0,87	0,69	-0,29	1

(B) **Intercropping**

Figure 6.5: Correlations showing associations of evaluated traits under sole cropping and intercropping

6.4 Discussion

The results demonstrated significant interactive effects of season, legume species, and cropping system on the phenological traits of legume crops. Intercropping enhanced emergence in several legumes during the second season, with the most noticeable improvements observed in Bambara groundnut and cowpea, showing increases of 9.8% and 12.0%, respectively, compared to sole cropping. Similarly, common bean emergence increased from 69.8% under sole cropping to 79.7% when intercropped. These findings are consistent with previous studies indicating that intercropping improves microclimatic conditions, enhances soil structure, and promotes more efficient resource utilization, thereby supporting more vigorous and uniform emergence (Chimonyo et al., 2020; Maitra et al., 2021; Kebede, 2021). In contrast, pigeon pea exhibited a decline in emergence to 68.1% under sole cropping in the second season. This reduction reflects patterns commonly observed in cereal–pigeon pea intercrops, where the slower early establishment of pigeon pea renders it susceptible to competitive suppression by the faster-growing cereal component, particularly during the early vegetative phase. This asymmetric competition often limits resource acquisition (e.g., light, nutrients, and water) by pigeon pea, thereby constraining its early growth and development (Demie et al., 2022). These observations underscore the potential of intercropping systems to enhance early establishment in certain legume species, though the benefits may not be uniformly realized across all legumes.

Intercropping significantly influenced the phenological development of the legume species studied. Pigeon pea exhibited an acceleration in development under intercropping conditions. In the first season, flowering and podding occurred approximately 51 and 50 days earlier, respectively, with similar trends observed in the second season. This acceleration may be attributed to stress-induced phenological shifts or improved environmental conditions within the intercrop, as previously reported by Kuyah et al. (2021), who found that intercropping reduced time to maturity in pigeon pea when grown with cereals. Early maturing legumes such as common bean and cowpea also showed significant reductions in the time to flowering and podding under intercropping. Similar results were reported by Pierre et al. (2024) in maize–cowpea intercropping systems, where enhanced light interception and improved soil moisture retention facilitated earlier reproductive development. In contrast, Bambara groundnut showed phenological stability across cropping systems and seasons. Flowering occurred between 48.1 and 51.2 days, and podding between 68.1 and 70.2 days, suggesting that its development is relatively insensitive to intercropping. This is consistent with findings by Kendabie et al. (2020), who reported that Bambara groundnut phenology is primarily regulated by photoperiod and genetic factors rather than by planting environment. These findings demonstrate that intercropping can accelerate phenological development in both early- and late-maturing legume species, likely through improved microenvironmental conditions, moderated interspecific competition, and enhanced resource-use efficiency. However, the extent of this response is species dependent.

Across all legume crops and growing seasons, intercropping consistently resulted in a higher number of pods per plant than sole cropping, indicating enhanced reproductive performance under intercrop conditions. In the 2022/23 season, pigeon pea recorded the highest number of pods per plant under intercropping. Cowpea and Bambara groundnut also exhibited substantial gains, with cowpea increasing by 31.9% and Bambara groundnut by 73.4%. Common bean followed a similar pattern, with a 42.7% increase in pod number under intercropping. These findings align with previous studies (Nassary et al., 2020; Suhi et al., 2022; Saad et al., 2022) and suggest that intercropping enhances resource availability and utilization, likely through complementary resource use, reduced intra-specific competition, and improved microclimatic conditions (Maitra et al., 2021).

This trend was also observed in the 2023/24 season, during which cowpea recorded the highest number of pods per plant under intercropping, followed by pigeon pea. Bambara groundnut exhibited the most significant seasonal improvement in pod number under sole cropping. This response may be attributed to residual soil fertility, favorable seasonal climatic conditions, or gradual genotype acclimatization over time (Kendabie et al., 2020). The consistent superiority of intercropping over sole cropping in enhancing pod production corroborates previous research reporting improvements in legume yield components under cereal–legume intercropping systems (Chimonyo et al., 2020; Demie et al., 2022). Increased pod production under intercropping is often linked to enhanced biological nitrogen fixation, moderated canopy temperatures, and more efficient spatial resource partitioning (Kebede, 2021; Kuyah et al., 2021). The significant interactions observed underscore the necessity of selecting cultivars with traits compatible with specific cropping system configurations to maximize interspecific complementarities and mitigate competition.

Pod mass and the number of seeds per pod were significantly influenced by legume species and cropping systems, indicating strong genetic and agronomic control over these reproductive traits. While interactions for pod mass were not significant, the number of seeds per pod interactions were highly significant, suggesting species-specific responses to intercropping arrangements. Intercropping consistently enhanced pod mass across all four legume crops in both growing seasons, reaffirming its potential to improve resource-use efficiency and reproductive development. In the 2022/23 season, cowpea recorded the highest increase in pod mass under intercropping. Common bean and Bambara groundnut also responded positively. Although pigeon pea typically produces smaller pods, it also exhibited an increase from intercropping. These benefits were maintained in the 2023/24 season, with particularly strong responses observed in pigeon pea and common bean. In contrast, Bambara groundnut showed minimal variation across both seasons and cropping systems, indicating a limited response to intercropping. This stability suggests that Bambara groundnut's yield characteristics may be more strongly governed by genetic and photoperiodic factors than by environmental or management-induced variability (Kendabie et al., 2020).

The number of seeds per pod also improved under intercropping for most species. In 2022/23, cowpea achieved the highest seed count. Pigeon pea and common bean followed similar trends, while Bambara groundnut increased modestly. These improvements are consistent with previous findings indicating that intercropping can enhance pollination efficiency, nutrient acquisition, and overall reproductive success through favorable microclimatic effects and complementary resource use (Maitra et al., 2021; Nassary et al., 2020). In 2023/24, this trend persisted: pigeon pea and common bean again exhibited an increased seed number under intercropping, and cowpea maintained the highest values. Bambara groundnut exhibited a minor decline in seed number under intercropping in the second season, further supporting its relative insensitivity to changes in cropping system. These results align with the literature demonstrating that intercropping can enhance yield components such as pod mass and seed number by improving biological nitrogen fixation, moderating canopy temperatures, and facilitating more efficient spatial and temporal resource partitioning (Seidel et al., 2022; Kuyah et al., 2021). However, the magnitude of these benefits remains species-specific and is closely dependent on the compatibility between cultivar traits and the cropping environment (Chimonyo et al., 2020; Demie et al., 2022). Understanding these interactions is essential for optimizing legume performance in diverse agroecological contexts.

The 100-seed weight was significantly influenced by both legume species and cropping system, with highly significant three-way interactions among cultivar, cropping system, and season. These findings underscore the critical roles of genetic factors and agronomic management in regulating seed development and final grain weight in legumes. In the 2022/23 season, all four legume species exhibited increased 100-seed weight under intercropping compared to sole cropping, suggesting enhanced resource-use efficiency and improved seed filling. Bambara groundnut recorded the highest seed weight under intercropping, reflecting a 15.1% increase, followed by common bean, cowpea, and pigeon pea. These results are consistent with previous findings (Audu, 2020; Pierre et al., 2024; Nyagumbo et al., 2025). The observed improvements likely reflect enhanced nutrient availability, reduced intra-specific competition, and moderated environmental stress under intercropping conditions (Maitra et al., 2021; Seidel et al., 2022).

A similar trend was observed in the 2023/24 season. Bambara groundnut again exhibited the highest seed weight and remained consistently responsive to intercropping, followed by cowpea and pigeon pea. These responses support previous studies that intercropping can enhance assimilate partitioning during grain filling by improving light interception and below-ground resource capture (Kuyah et al., 2021; Demie et al., 2022). However, not all legume crops responded homogeneously. In contrast to its positive response in the prior season, common bean displayed a slight decline in 100-seed weight under intercropping in 2023/24. This reduction may be attributed to increased interspecific competition during the reproductive stage or to suboptimal spatial or temporal niche complementarity, which may have limited its ability to efficiently allocate resources to seed development (Chimonyo et al., 2020; Nassary et al., 2020). The consistent performance of Bambara groundnut suggests inherent physiological robustness and strong adaptation to intercrop environments.

Intercropping systems demonstrated higher land productivity, with land equivalent ratios (LER) consistently exceeding 1.0 across all four legume species in both growing seasons, indicating that legume-based intercropping can enhance land-use efficiency and yield performance. These results agree with the findings of Phiri and Dixon (2024) and Adam et al. (2025). In the 2022/23 season, cowpea showed the highest LER, followed by Bambara groundnut, pigeon pea, and common bean. These findings are consistent with existing literature demonstrating the superior land-use efficiency of intercropping systems (Maitra et al., 2021; Seidel et al., 2022; Nassary et al., 2020). The consistently high LER values observed for cowpea across both seasons highlight its compatibility with intercropping, likely due to its early maturity, rapid canopy establishment, and efficient resource use (Kuyah et al., 2021; Pierre et al., 2024). In contrast, the seasonal variability in Bambara groundnut's LER suggests a greater sensitivity to environmental conditions and competitive dynamics, which may influence its productivity in mixed stands. The study confirms that intercropping can significantly enhance land-use efficiency across a range of legume crops. However, the extent of the benefit is species- and season-dependent. Optimizing intercrop performance requires cautious selection of compatible crop combinations, taking into account phenology, growth patterns, and spatial niche differentiation (Demie et al., 2022; Chimonyo et al., 2020). Integrating neglected legumes such as Bambara groundnut into intercropping systems represents a promising strategy to strengthen agricultural sustainability and resilience in sub-Saharan Africa.

These findings suggest that intercropping enhances overall productivity in rainfed systems, likely through more efficient resource use, complementary species interactions, and reduced interspecific competition relative to sole cropping. Cowpea exhibited the greatest response to intercropping, which may be attributed to its early maturity and strong adaptability to competitive environments. Common bean and Bambara groundnut also showed substantial yield improvements. Notably, Bambara groundnut, despite its slower growth and extended reproductive cycle, recorded yield increases exceeding 0.3 t ha^{-1} under intercropping in both seasons, indicating that its physiological traits, such as drought tolerance and deep rooting—are well-suited to intercrop systems. Pigeon pea exhibited the smallest, yet consistent, yield improvements under intercropping. Although less responsive than the other species, its positive trend suggests that pigeon pea can still benefit from intercropping, potentially due to its complementary rooting depth and long growth duration, which may facilitate temporal niche differentiation. These findings underscore the potential of intercropping as a viable strategy to improve the productivity of neglected legume species in smallholder rainfed systems.

6.4.1 Conclusion, Recommendations and Future Directions

This study demonstrates that cropping systems, particularly legume-based intercropping, significantly influence the adaptability and productivity of neglected legumes under rainfed conditions. Interactive effects of season, cultivar, and cropping system were evident on key phenological traits, with intercropping enhancing early emergence and accelerating reproductive development in legumes such as Bambara groundnut, cowpea, and common bean, while pigeon pea showed reduced establishment under sole cropping due to competitive suppression. Pod production, pod mass, seed number per pod, 100-seed weight and grain yield were consistently improved under intercropping, reflecting enhanced resource-use efficiency, moderated microclimatic stress, and reduced intra-specific competition. Cowpea and Bambara groundnut exhibited strong and stable responses across seasons, whereas common bean and pigeon pea displayed more variable results, highlighting the importance of genotype-specific and species-specific compatibility with intercrop designs. Land equivalent ratio (LER) consistently exceeded 1.0 across legume species, confirming that intercropping increases land-use efficiency and yield potential in smallholder agroecosystems. Cowpea exhibited the highest grain yield (t ha^{-1}) under intercropping, followed by Bambara groundnut, while moderate yield improvements were observed for pigeon pea and common bean. Based on these results, the study recommends cowpea–maize intercropping as a promising strategy for enhancing productivity in rainfed smallholder systems. These findings underscore the need for strategic selection of legume species with complementary phenology, growth dynamics, and resource requirements to optimize interspecific interactions and system productivity. It is recommended that future research focus on unravelling the physiological, morphological, and genetic mechanisms underlying species-specific responses to intercropping, including hormonal regulation, root and canopy architecture, and source–sink dynamics. Long-term studies assessing soil fertility impacts, genotype-by-environment interactions, and resilience under diverse agroecological contexts are essential to refine intercropping strategies that support sustainable intensification and food security in rainfed smallholder farming systems.

References

1. Abobatta, W.F., El-Hashash, E.F. and Hegab, R.H., 2021. Challenges and opportunities for the global cultivation and adaptation of legumes. Journal of Applied Biotechnology & Bioengineering, 8(5), pp.160-172.
2. Abobatta, W.F., Hegab, R.H. and El-Hashash, E.F., 2022. Challenges and opportunities for the global cultivation and adaptation of legumes B. Opportunities for increasing legumes production and availability. Annals of Agricultural & Crop Sciences, 7(1), p.1107.
3. Adam, A.M., Giller, K.E., Rusinamhodzi, L., Rasche, F., Koomson, E., Marohn, C. and Cadisch, G., 2025. Enhancing the resilience of intercropping systems to changing moisture conditions in Africa through the integration of grain legumes: A meta-analysis. Field Crops Research, 321, p.109663.)
4. Adelabu, D.B. and Franke, A.C., 2023. Research status of seed improvement in underutilized crops: Prospects for enhancing food security. The Journal of Agricultural Science, 161(3), pp.398-411.
5. Audu, I., 2020. Growth and Yield Performance of Bambara nuts (Vigna subterranean (L). Verdc) as Influenced by Cropping System and Plant Spacing in Yola, Nigeria. Journal of Sustainable Agriculture and the Environment (JSAE), 18(1), pp.136-151.
6. Ayilara, M.S., Abberton, M., Oyatomi, O.A., Odeyemi, O. and Babalola, O.O., 2022. Potentials of underutilized legumes in food security. Frontiers in Soil Science, 2, p.1020193.
7. Baker, E., Kerr, R.B., Deryng, D., Farrell, A., Gurney-Smith, H. and Thornton, P., 2023. Mixed farming systems: potentials and barriers for climate change adaptation in food systems. Current Opinion in Environmental Sustainability, 62, p.101270.
8. Bitew, Y., Derebe, B., Worku, A. and Chakelie, G., 2021. Response of maize and common bean to spatial and temporal differentiation in maize-common bean intercropping. PLoS One, 16(10), p.e0257203)
9. Chandra, M.S., Naresh, R.K., Thenua, O.V.S., Singh, R. and Geethanjali, D., 2020. Improving resource conservation, productivity and profitability of neglected and underutilized crops in the breadbasket of India: A review. Breeding Science, 70(1), pp.19-31.
10. Chimonyo, V.G., Wimalasiri, E.M., Kunz, R., Modi, A.T. and Mabhaudhi, T., 2020. Optimizing traditional cropping systems under climate change: a case of maize landraces and Bambara groundnut. Frontiers in sustainable food systems, 4, p.562568.
11. Demie, D.T., Döring, T.F., Finckh, M.R., van der Werf, W., Enjalbert, J. and Seidel, S.J., 2022. Mixture× genotype effects in cereal/legume intercropping. Frontiers in Plant Science, 13, p.846720.
12. Dimande, P., Arrobas, M. and Rodrigues, M.Â., 2024. Intercropped maize and cowpea increased the land equivalent ratio and enhanced crop access to more nitrogen and phosphorus compared to cultivation as sole crops. Sustainability, 16(4), p.1440.
13. Gomez, K.A. and Gomez, A.A., 1984. Statistical procedures for agricultural research. John wiley & sons.
14. Hirpa, T., 2014. Effect of intercrop row arrangement on maize and haricot bean productivity and the residual soil. World Journal of Agricultural Sciences, 4, pp.69-77.

15. Icka, P. and Damo, R., 2023. Neglected and underutilized crop species a path to improving nutritional security and diversification of agriculture. Mechanization in agriculture & Conserving of resources, 67(1), pp.22-26.
16. Kebede, E., 2021. Contribution, utilization, and improvement of legumes-driven biological nitrogen fixation in agricultural systems. Frontiers in Sustainable Food Systems, 5, p.767998.
17. Kendabie, P., Jørgensen, S.T., Massawe, F., Fernandez, J., Azam-Ali, S. and Mayes, S., 2020. Photoperiod control of yield and sink capacity in Bambara groundnut (Vigna subterranea) genotypes. Food and Energy Security, 9(4), p.e240.
18. Kuyah, S., Sileshi, G.W., Nkurunziza, L., Chirinda, N., Ndayisaba, P.C., Dimobe, K. and Öborn, I., 2021. Innovative agronomic practices for sustainable intensification in sub-Saharan Africa. A review. Agronomy for Sustainable Development, 41, pp.1-21.
19. Li, X., Yadav, R. and Siddique, K.H., 2020. Neglected and underutilized crop species: the key to improving dietary diversity and fighting hunger and malnutrition in Asia and the Pacific. Frontiers in Nutrition, 7, p.593711.
20. Maitra, S., Hossain, A., Brestic, M., Skalicky, M., Ondrisik, P., Gitari, H., Brahmachari, K., Shankar, T., Bhadra, P., Palai, J.B. and Jena, J., 2021. Intercropping—A low input agricultural strategy for food and environmental security. Agronomy, 11(2), p.343.
21. Mihrete, T.B. and Mihretu, F.B., 2025. Crop Diversification for Ensuring Sustainable Agriculture, Risk Management and Food Security. Global Challenges, p.2400267.
22. Mthembu, B.E., Cele, T. and Mkhize, X., 2025. Climate Change Impacts on Agricultural Infrastructure and Resources: Insights from Communal Land Farming Systems. Land, 14(6), p.1150.
23. Mukhovi, S. and Jacobi, J., 2022. Can monocultures be resilient? Assessment of buffer capacity in two agro-industrial cropping systems in Africa and South America. Agriculture & Food Security, 11(1), p.19.
24. Naresh, R., Chandra, M.S., Mahajan, N.C., Singh, P.K., Baliyan, A., Ahlawat, P. and Shalini, P., 2021. Neglected and underutilized crop species the key to improving soil nutritional security for fighting poverty, hunger and malnutrition in north-western IGP: a review. Journal of Pharmaceutical Innovation, 10(8), pp.1833-1839.
25. Nassary, E.K., Baijukya, F. and Ndakidemi, P.A., 2020. Productivity of intercropping with maize and common bean over five cropping seasons on smallholder farms of Tanzania. European Journal of Agronomy, 113, p.125964.
26. Njira, K.O., Semu, E., Mrema, J.P. and Nalivata, P.C., 2021. Productivity of pigeon pea, cowpea and maize under sole cropping, legume–legume and legume–cereal intercrops on Alfisols in Central Malawi. Agroforestry Systems, 95(2), pp.279-291.
27. Nkhata, W., Shimelis, H. and Chirwa, R., 2021. Productivity of newly released common bean (Phaseolus vulgaris L.) varieties under sole cropping and intercropping with maize (Zea mays L.). Frontiers in Sustainable Food Systems, 5, p.741177.
28. Nyagumbo, I., Nyamayevu, D. and Silva, J.V., 2025. Food and nutrition security merits of intercropping maize, sorghum and millet with legumes on small farms in Southern Africa. Food Security, pp.1-16.)
29. Odeku, O.A., Ogunniyi, Q.A., Ogbole, O.O. and Fettke, J., 2024. Forgotten gems: exploring the untapped benefits of underutilized legumes in agriculture, nutrition, and environmental sustainability. Plants, 13(9), p.1208.

30. Phiri, A., Njira, K. and Dixon, A., 2024. Comparative effects of legume-based intercropping systems involving pigeon pea and cowpea under deep-bed and conventional tillage systems in Malawi. Agrosystems, Geosciences & Environment, 7(2), p.e20503.
31. Pierre, J.F., Singh, U., Latournerie–Moreno, L., Garruña, R., Jacobsen, K.L., Ruiz–Santiago, R.R., Chan–Arjona, A.D. and Ruiz–Sánchez, E., 2024. Effect of Different Maize (*Zea mays*)/Cowpea (*Vigna unguiculata*) Intercropping Patterns and N Supply on Light Interception, Physiology and Productivity of Cowpea. Agricultural Research, 13(2), pp.204-215.
32. Popoola, J., Ojuederie, O. and Omonhinmin, C., 2020. Neglected and Underutilized Legume Crops: Improvement and. Recent advances in grain crops research, p.123.
33. Renwick, L.L., Kimaro, A.A., Hafner, J.M., Rosenstock, T.S. and Gaudin, A.C., 2020. Maize-pigeonpea intercropping outperforms monocultures under drought. Frontiers in Sustainable Food Systems, 4, p.562663.)
34. Rokka, S., El Bilali, H., Borelli, T., Calabrese, G.J., Lecci, S., Otieno, G., Tietiambou, F.R.S., Bteich, M.R., Grazioli, F., Kabre, B. and Seindira, M., 2025. Current policies for promoting neglected and underutilized crop species in Burkina Faso and Niger. International Journal of Agricultural Sustainability, 23(1), p.2459541.
35. Saad, A.H., El Naim, A.M., Ahmed, A.A., Ibrahim, K.A., Islam, M.S., Al-Qthanin, R.N. and Idris, A.M., 2022. Response of sesame to intercropping with groundnut and cowpea. Communications in Soil Science and Plant Analysis, 53(17), pp.2285-2296.
36. Suhi, A.A., Mia, S., Khanam, S., Mithu, M.H., Uddin, M.K., Muktadir, M.A., Sultan, A. and Jindo, K., 2022. How Does Maize-Cowpea Intercropping Maximize Land Use and Economic Return? A Field Trial in Bangladesh. Land, 11(4), p.581.)
37. Teklemariam, E., Yoseph, T. and Ayalew, T., 2025. Agronomic performance and profitability of maize and cowpea intercropping as affected by increased rows of cowpea in Ethiopia. Crop, Forage & Turfgrass Management, 11(1), p.e70047)
38. Templer, N., Gatwiri, J., Nchanji, E., Gichuru, L., Puozaa, D. and Ojiewo, C., 2025. National breeding programs and variety release processes: A systematic review of how the interactions shape diversity and adoption of dryland legumes and cereals in Africa. Outlook on Agriculture, p.00307270241313230.
39. Tetteh, A., Kusi, F., Adu-Gyamfi, R. and Attamah, P., 2021. Evaluation of the Suitability of Some Cowpea Genotype for Maize-Cowpea Intercrop in Northern Ghana. American Journal of Plant Sciences, 12(12), pp.1817-1834)
40. Vilakazi, B., Mafongoya, P.L., Odindo, A.O. and Phophi, M.M., 2025. The role of neglected grain legumes in Food and Nutrition Security and Human Health. Sustainability, 17(1), p.350.
41. Vilakazi, B., Odindo, A.O., Phophi, M.M. and Mafongoya, P.L., 2025. Socioeconomic Factors Influencing Crop Diversification Among Smallholder Farmers in Bergville, South Africa. Agriculture, 15(9), p.914.

Chapter 7: Conclusions and Recommendations

7.1 Introduction

This study explored the potential of integrating neglected legumes into smallholder cropping systems as a pathway to promote food security, climate resilience, and sustainable production in line with the United Nations Sustainable Development Goal 2 (Zero Hunger). Neglected legumes such as Bambara groundnut, and cowpea, and pigeon pea offer unique advantages due to their adaptability to low-input, rainfed environments. However, their cultivation remains limited by socioeconomic, institutional, and agronomic constraints. This chapter synthesizes the key findings from the preceding chapters, discusses their broader implications, and provides integrated conclusions and recommendations to guide future research, policy, and smallholder practice.

The findings from the socioeconomic (Chapters 3-4) and agronomic (Chapters 5-6) components collectively highlight that both human and biophysical factors shape the successful integration of neglected legumes into smallholder farming systems. Socioeconomic results revealed that diversification decisions are primarily influenced by access to land and water, education, market opportunities, and household demographics. Notably, older farmers were more likely to engage in diversification, whereas youth participation remained limited due to perceptions of farming as a low-status or unprofitable activity. This highlights the need for targeted youth engagement strategies and inclusive extension support to revitalize legume-based farming. Chapters 4–6 demonstrated that while biophysical factors such as rainfall, and planting date strongly affect performance, the adoption of neglected legumes is also constrained by limited awareness of their nutritional and agronomic value. The participatory training and demonstration trials substantially improved farmer willingness to adopt and integrate these crops, confirming that knowledge-based interventions can shift attitudes and practices toward diversification.

Across the two growing seasons, agronomic trials revealed distinct species-specific responses to planting date and cropping systems. Early planting enhanced establishment and vegetative growth in all species, primarily due to favorable early-season moisture and temperature conditions. However, reproductive performance varied: cowpea and Bambara groundnut maintained stable yields across planting dates, while common bean and pigeon pea were more sensitive to delayed sowing and environmental fluctuations. These findings underscore the importance of adaptive planting strategies rather than fixed sowing dates, particularly under variable rainfall. The use of staggered planting and seasonal climate forecasts can support alignment between crop phenology and favorable moisture conditions, reducing risk of yield loss. Intercropping proved beneficial for all legumes, improving resource-use efficiency and yield stability, as indicated by Land Equivalent Ratios greater than 1.0. Cowpea and common bean showed strong positive responses due to their early canopy development, while Bambara groundnut and pigeon pea benefited from reduced competition and improved moisture use. These results validate intercropping as a viable, low-input intensification strategy for smallholder rainfed systems.

The socioeconomic and agronomic insights from this study demonstrate that diversification with neglected legumes can simultaneously address productivity, resilience, and nutritional challenges in smallholder systems. However, scaling adoption requires both social and technical interventions. Farmer training, improved access to seed and markets, and support for community-based seed systems are essential to overcome barriers of knowledge and input availability. From an ecological perspective, neglected legumes such as Bambara groundnut and cowpea offer robust adaptation to climate variability due to their phenological flexibility and modest input requirements. Their inclusion in intercropping systems not only enhances food production but also offers long-term benefits to degraded rainfed lands.

7.2 Conclusion

This study provides a comprehensive evaluation of the agronomic and socioeconomic determinants influencing crop diversification and the adoption of neglected legumes in smallholder rainfed farming systems in South Africa. The findings indicate that farmers' decisions to cultivate neglected legumes, namely Bambara groundnut *(Vigna subterranea)*, cowpea (*Vigna unguiculata*), and pigeon pea (*Cajanus cajan*), as well as common bean (*Phaseolus vulgaris*) are shaped by multiple factors, including household size, marital status, access to irrigation, farming experience, and exposure to legume-related training programs. Limited cultivation of neglected legumes was attributed more to inadequate awareness of their agronomic and nutritional benefits than to biophysical or economic resource constraints. The implementation of knowledge-based interventions, such as targeted training and on-farm demonstrations, substantially increased farmers' willingness to cultivate these species, including among those previously reliant on monoculture. These findings underscore the potential of capacity-building initiatives to promote diversified, resilient cropping systems.

Agronomic trials conducted over two growing seasons under rainfed conditions revealed that planting date significantly affects the phenological development and yield components of neglected legumes, with responses varying by species and season. Early planting improved crop establishment, particularly for Bambara groundnut and cowpea, which also demonstrated stable reproductive performance across planting dates. In contrast, common bean exhibited high sensitivity to sowing time, while pigeon pea showed poor adaptability to delayed planting, likely due to its long growth cycle and photoperiod dependence. Moreover, cropping systems, particularly legume-based intercropping, significantly influence the adaptability and productivity of neglected legumes under rainfed conditions. Intercropping enhanced early emergence and accelerated reproductive development in Bambara groundnut, cowpea, and common bean, while pigeon pea exhibited reduced establishment under sole cropping due to competitive suppression. Yield components such as pod production, pod mass, seed number per pod, and 100-seed weight improved under intercropping, enhancing resource-use efficiency and moderated microclimatic stress.

7.3 Recommendations

To support the integration of neglected legumes into climate-smart agriculture, the study recommended the development of enabling policy environments that promote market access, value chain development, and extension services focused on underutilized crops. Engaging youth through dedicated training programs and addressing structural barriers to participation are essential for long-term adoption. Furthermore, mainstreaming crop diversification into local development plans could enhance food and nutritional security and contribute to the resilience of smallholder farming systems. Future research should prioritize longitudinal studies on the agronomic and economic impacts of diversification, assess the potential of improved cultivars and digital tools, and adopt gender-sensitive approaches to address social disparities in adoption. Such efforts are critical for scaling neglected legumes as a pathway toward sustainable intensification in rainfed agricultural systems. The study further recommended that, in rainfed smallholder farming systems characterized by climatic variability, selecting appropriate planting dates is essential to ensure optimal crop establishment and alignment of critical growth stages with favorable environmental conditions. It is also recommended that future research focus on elucidating the physiological, morphological, and genetic mechanisms underlying species-specific responses to intercropping, particularly aspects such as hormonal regulation, root and canopy architecture, and source–sink dynamics. These insights will be critical for designing resilient intercropping systems that optimize productivity and adaptability under variable agroecological conditions.

APPENDIX A: INFORMATION ON APPENDICES

The below ethical clearance for this study was obtained from the University of KwaZulu-Natal Ethics Committee, facilitated by the School of Agricultural, Earth, and Environmental Sciences, under reference number HSSREC/00008179/2025.

Ethical Clearance
Approval - Ms Busisiw