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**Comparative analysis of total factor
productivity of Neglected and Underutilized
versus Staple Crops: Implications for
sustainable food systems in Uganda and
South Africa**

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Abstract

Agricultural productivity in Sub-Saharan Africa is largely focused on a few staple crops, including maize and rice, with their productivity increasingly affected by climate, soil, and resource use issues. In contrast, neglected and underutilized crops, including sorghum, finger millet, cowpea, and groundnut, have drought resistance, lower resource requirements, and high nutritional benefits, yet they have been ignored in research and policy development. While there is evidence of sustainability benefits associated with neglected and underutilized crops, there is limited evidence on their relative economic productivity to staple crops at the national level in Sub-Saharan Africa. This research aims to address this gap in knowledge with a comparative analysis of Total Factor Productivity (TFP) of neglected and underutilized crops relative to staple crops in Uganda and South Africa.

The research used a sequential mixed-methods approach with Phase I consisting of an Integrative Literature Review of 38 sources between 2010 and 2025 to provide a comprehensive synthesis of evidence on the sustainability contributions of NUCs to climate resilience, soil health, resource use, and nutrition, among other benefits. while Phase II used Data Envelopment Analysis (DEA) to estimate static technical efficiencies, with the Malmquist Productivity Index applied to estimate inter-temporal changes in TFP with components of Efficiency Change (Effch) and Technical Change (Techch). The research was conducted on a harmonized balanced panel dataset from FAOSTAT, UBOS, and Statistics South Africa from 2010 to 2022, with three staple crops (maize, beans, and rice) and four neglected and underutilized crops (finger millet, sorghum, cowpea, and groundnut). In addition, partial productivity ratios were estimated to supplement the analysis of multi-factor efficiencies.

The findings of the analysis highlight three key outcomes. Firstly, TFP parity: the productivity of NUCs is statistically similar to that of staple crops in both nations, with $p > 0.05$. This questions the economic inferiority of NUCs. Secondly, regional differentiation: the productivity dynamics of South Africa are characterized by technological progress, with MPI ≈ 1.04 – 1.12 , and Techch > 1 , while Uganda records stagnant productivity, with MPI ≈ 0.96 , relying on efficiency change to support the productivity of NUCs, with Effch > 1 . Thirdly, differentiation in input usage: the study finds that staple crops register higher absolute yields with intensive input usage, while NUCs maintain overall efficiency with lower external input usage.

The research shows that NUCs can produce comparable productivity at much lower input intensity, thus making NUCs economically viable components of sustainable intensification and climate-smart agriculture. By shifting the productivity debate from yield maximization to resource use efficiency, this research offers evidence to support context-specific diversification policies in Uganda and South Africa for building resilience in their food systems.

Keywords: Neglected and Underutilized Crops; Staple Crops; Total Factor Productivity; Data Envelopment Analysis; Malmquist Index; Efficiency Change; Technological Change; Sustainable Intensification; Uganda; South Africa.

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List of abbreviations

General & Theoretical Terms

AIVs: African Indigenous Vegetables
CSA: Climate-Smart Agriculture
GHG: Greenhouse Gas
NUCs: Neglected and Underutilized Crops
SCs: Staple Crops
SDGs: Sustainable Development Goals
SFS: Sustainable Food Systems
SI: Sustainable Intensification
SSA: Sub-Saharan Africa

Methodological & Metric Abbreviations

CRS: Constant Returns to Scale
DEA: Data Envelopment Analysis
DMU: Decision Making Unit
Effch: Efficiency Change
HFIAS: Household Food Insecurity Access Scale
ILR: Integrative Literature Review
LER: Land Equivalent Ratio
MPI: Malmquist Productivity Index
OR: Odds Ratio
PPF: Production Possibility Frontier
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SAP: Sustainable Agricultural Productivity
SFA: Stochastic Frontier Analysis
TFP: Total Factor Productivity
TFPCH: Total Factor Productivity Change
Techch: Technological Change
VRS: Variable Returns to Scale
WPI: Water Poverty Index
WUE: Water Use Efficiency

Organizations, Regional Contexts & Currencies

ARC: Agricultural Research Council (South Africa)
DAAD: German Academic Exchange Service (*Deutscher Akademischer Austauschdienst*)
FAO: Food and Agriculture Organization of the United Nations
FAOSTAT: Food and Agriculture Organization Corporate Statistical Database
FSIN: Food Security Information Network
IPC/CH: Integrated Food Security Phase Classification / Cadre Harmonisé
NARO: National Agricultural Research Organisation (Uganda)
STIBET: Scholarship Program of the DAAD
Stats SA: Statistics South Africa
UBOS: Uganda Bureau of Statistics
UGX: Ugandan Shilling
USD: United States Dollar

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Chapter 1: Introduction

The global food system is under increasing strain from the combined pressures of population growth, climate change, and persistent food insecurity. Feeding a projected global population approaching 10 billion by 2050 will require not only increased agricultural production but also more efficient and sustainable use of natural resources (Godfray et al., 2010; United Nations, 2022). At the same time, agriculture remains highly vulnerable to climatic variability while contributing significantly to environmental degradation, highlighting the need for production systems that are both productive and resilient (Tilman et al., 2017).

Despite these challenges, agricultural development strategies have remained heavily concentrated on a narrow range of staple crops such as maize, rice, and wheat. While these crops are central to food security, their dominance has reinforced input-intensive production systems that are often unsustainable under conditions of resource scarcity (Pretty et al., 2018; Lin, 2011). This focus has also shaped how productivity is conceptualised and measured, with emphasis placed primarily on yield rather than on the efficiency with which inputs are transformed into outputs.

In contrast, neglected and underutilised crops (NUCs) including sorghum, finger millet, cowpea, and groundnuts have historically received limited attention in research and policy frameworks. These crops are well adapted to marginal environments and exhibit resilience to drought, low soil fertility, and other climatic stresses (Mabhaudhi et al., 2019; Tadele, 2019). In addition, they contribute to dietary diversity and improved nutrition, particularly in regions where micronutrient deficiencies remain widespread (Chivenge et al., 2015). However, despite these advantages, NUCs continue to be marginalised in agricultural development strategies.

A key reason for this marginalisation is the lack of robust empirical evidence on their economic performance. Existing studies tend to focus on the ecological and nutritional benefits of NUCs while providing limited analysis of their productivity relative to staple crops. Where comparisons are made, they are often based on yield, which does not account for differences in input use and may therefore underestimate the efficiency of crops grown under low-input conditions. This yield-focused approach has reinforced a perception that NUCs are inherently less productive and therefore less worthy of investment in research, extension services, or agricultural policy. Yet this perception has not been adequately tested using comprehensive, efficiency-based productivity measures that account for the range of inputs employed in crop production.

This highlights a critical gap in the literature: the absence of comprehensive productivity assessments that evaluate NUCs using metrics capable of capturing both input-use efficiency and technological change. Total Factor Productivity (TFP) provides such a framework by measuring output relative to a bundle of inputs, thereby offering a more complete assessment of agricultural performance (Coelli & Rao, 2005; Fuglie, 2015). However, the application of TFP analysis to NUCs remains limited, particularly in comparative and cross-country contexts. Data limitations and the exclusion of these crops from official statistics have further constrained their inclusion in productivity analysis (Fuglie & Rada, 2013), creating a structural

bias that favours well-documented staple crops and limits the visibility of alternative production systems.

Against this background, this study provides a comparative TFP analysis of NUCs and staple crops in Uganda and South Africa. The two countries represent contrasting agricultural systems: Uganda is characterised by predominantly smallholder, low-input farming, while South Africa has a more commercialised and technology-intensive agricultural sector. This contrast provides an opportunity to examine whether the relative productivity performance of NUCs is context-dependent and to distinguish the roles of efficiency change and technological change across different production environments.

The primary objective of this study is to evaluate the economic viability of neglected and underutilised crops relative to staple crops by comparing their Total Factor Productivity in Uganda and South Africa over the period 2010–2022. Specifically, the study aims to: (1) synthesise literature-based evidence on the sustainability characteristics of neglected and underutilised crops and their implications for productivity assessment; (2) estimate and compare the Total Factor Productivity of neglected and underutilised crops and staple crops in Uganda and South Africa; and (3) decompose productivity change into efficiency change and technological change to explain observed productivity differences.

Building on these objectives, the study addresses three research questions:

- i. What sustainability-related characteristics of neglected and underutilised crops suggest limitations of conventional yield-based productivity assessment?
- ii. Do neglected and underutilised crops achieve comparable Total Factor Productivity to staple crops?
- iii. To what extent do efficiency change and technological change explain observed productivity differences between neglected and underutilised crops and staple crops?

The study is guided by a conceptual framework that integrates Total Factor Productivity analysis within the broader context of sustainable agricultural intensification. Agricultural production is represented through a set of input and output variables, with inputs including land, labour, material inputs such as fertilizer, pesticides and irrigation, and capital in the form of mechanisation costs. The output variable is defined as crop yield per hectare, adjusted using real price data to reflect output value. By capturing a broad range of inputs, this approach moves beyond partial productivity indicators that dominate conventional crop comparisons and may systematically disadvantage low-input crops such as NUCs.

At the centre of the analytical framework is the Data Envelopment Analysis (DEA)-based Malmquist Productivity Index (MPI), which is used to measure TFP change over time. The Malmquist index decomposes TFP into efficiency change (Effch), which captures movement towards or away from the existing production frontier, and technological change (Techch), which captures shifts in the frontier itself. This decomposition allows productivity differences to be examined in relation to the contrasting production environments of Uganda and South Africa. The resulting productivity evidence is subsequently interpreted alongside four sustainability dimensions identified through the integrative literature review: climate resilience, soil health, resource-use efficiency, and food security and nutrition.

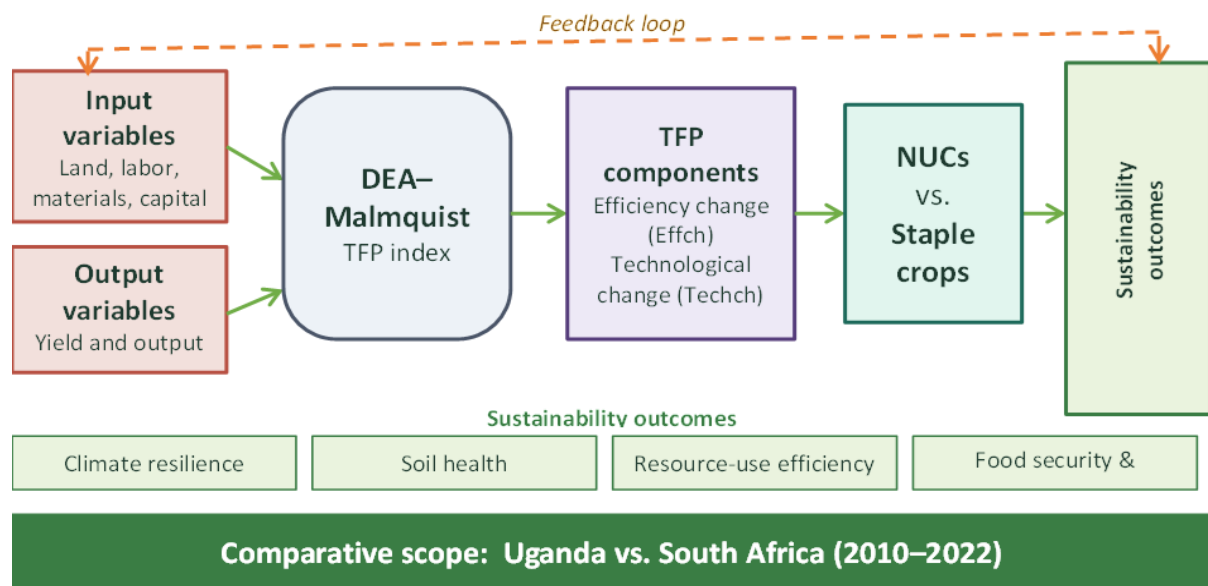


Figure 1: Conceptual Framework DEA-Malmquist TFP Analysis of NUCs vs. Staple Crops
Source: Author's framework based on Coelli & Rao (2005), Fuglie (2015), Mabhaudhi et al. (2019)

While Figure 1 presents the overall conceptual architecture of the study, the framework is operationalised through a sequence of analytical stages. Figure 2 illustrates this progression, beginning with the definition of agricultural inputs and outputs, followed by DEA-Malmquist estimation and the decomposition of TFP into efficiency and technological change. These stages provide the basis for comparing the productivity performance of NUCs and staple crops before the resulting evidence is interpreted alongside the sustainability dimensions identified through the literature review. Figure 2 therefore provides a bridge between the conceptual framework and the methodological procedures described in Section 3.

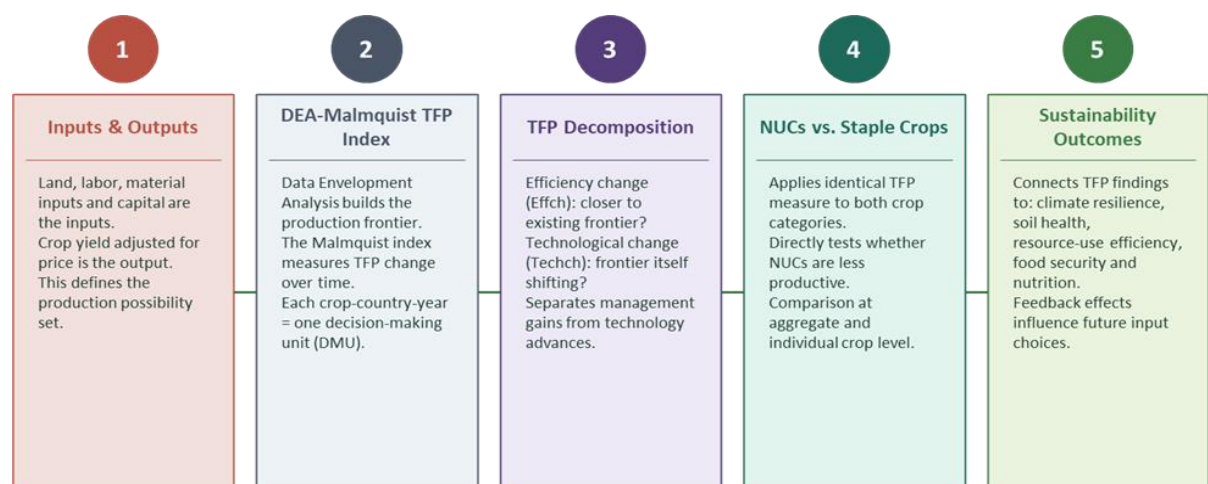


Figure 2: Five Analytical Stages of the Conceptual Framework from Inputs to Sustainability Outcomes
Source: Author's framework compilation

The contribution of this working paper is threefold. First, it extends productivity analysis to include NUCs, thereby addressing a significant gap in the agricultural economics literature. Second, it provides comparative evidence across distinct agricultural systems, enhancing the relevance of the findings for broader policy contexts. Third, it contributes to ongoing debates

on sustainable agriculture by demonstrating the importance of evaluating productivity in terms of efficiency rather than output alone.

The remainder of the paper is organised as follows. Section 2 reviews the literature on agricultural productivity, the dominance of staple crops in productivity analysis, and the role of NUCs in sustainable agriculture. Section 3 describes the methodology, including the integrative literature review and quantitative TFP analysis using the DEA-Malmquist framework. Section 4 presents and discusses the sustainability and empirical productivity results for Uganda and South Africa. Section 5 concludes and presents the policy and practical implications of the findings.

Chapter 2: Literature Review

This section reviews the relevant literature on agricultural productivity, with a particular focus on Total Factor Productivity as a comprehensive measure of performance. It situates the analysis within the broader context of agricultural systems in Sub-Saharan Africa, examining the dominance of staple crops and the emerging role of neglected and underutilized crops. The review further explores the limitations of existing productivity assessments, particularly the reliance on yield-based measures, and identifies key gaps in the empirical literature that motivate the present study.

2.1 Agricultural Productivity and Total Factor Productivity

Agricultural productivity is a central determinant of economic growth, poverty reduction, and food security, particularly in Sub-Saharan Africa where agriculture remains the backbone of rural livelihoods (Fuglie, 2015; Nin-Pratt & Yu, 2010). Traditionally, productivity has been assessed using partial indicators such as yield per hectare or labour productivity. However, these measures are limited in scope, as they fail to account for the joint contribution of multiple inputs in the production process.

A key strength of TFP analysis lies in its grounding in the concept of a production frontier, often referred to as the best-practice frontier. Within this framework, productivity improvements can arise through two distinct but related mechanisms. The first is efficiency change (catch-up), which reflects the ability of producers to move closer to the existing frontier by improving resource allocation and management practices. The second is technological change (innovation), which represents a shift of the frontier itself outward through the adoption of new technologies, improved varieties, or enhanced production techniques (Färe et al., 1994; Coelli et al., 2005).

This distinction is particularly important in the context of developing economies. Empirical evidence suggests that, in many Sub-Saharan African countries, TFP growth has historically been driven more by efficiency gains than by input expansion (Alston et al., 2010; Fuglie & Rada, 2013; Nin-Pratt et al., 2011). In smallholder systems characterized by limited access to capital and technology, improvements in productivity are often achieved through better use of existing resources rather than the adoption of new-to-the-world technologies. This has important implications for evaluating different crop systems, particularly those that operate under low-input conditions.

2.2 The Dominance of Staple Crops in Productivity Analysis

The literature on agricultural productivity has largely focused on staple crops such as maize, rice, and wheat, reflecting their central role in global food systems and policy priorities (Fuglie, 2018; Pingali, 2012). While this focus has generated significant advances in productivity, it has also reinforced a narrow production paradigm centred on input intensification and yield maximisation.

This paradigm has contributed to the expansion of monoculture systems, which are associated with declining soil fertility, increased pest vulnerability, and reduced biodiversity (Tilman et al., 2017; Khoury et al., 2014). In Sub-Saharan Africa, where access to inputs is often limited, such systems may not be sustainable or scalable (Pretty et al., 2018; Jayne et al., 2019). Moreover, yield-focused productivity assessments tend to favour crops that perform well under high-input conditions, potentially biasing policy and investment decisions against NUCs.

In addition, policy instruments such as subsidies for chemical fertilizers, hybrid seeds, and irrigation infrastructure frequently favor staple crop production. These interventions can create market distortions, making staple crops appear more profitable than they would be under market-neutral conditions (Jayne et al., 2019). Consequently, productivity comparisons based on observed output may reflect policy-induced advantages rather than inherent efficiency differences.

2.3 Neglected and Underutilised Crops in Sustainable Agriculture

Neglected and underutilized crops have gained increasing attention as potential contributors to sustainable and resilient agricultural systems (Mabhaudhi et al., 2019; Tadele, 2019). These crops are typically adapted to marginal environments characterized by low soil fertility, limited water availability, and high climatic variability. Their ability to maintain stable yields under such conditions has positioned them as key components of climate adaptation strategies (Chivenge et al., 2015).

However, the value of NUCs extends beyond their agronomic characteristics. From an agroecological perspective, these crops provide important ecosystem services, such as improving soil fertility through nitrogen fixation, enhancing biodiversity, and breaking pest and disease cycles when used in crop rotations (Snapp et al., 2010; Giller et al., 2021). These functions contribute to the long-term sustainability of agricultural systems, even if they are not fully captured in conventional productivity metrics.

NUCs also have significant social and cultural value, particularly in smallholder systems where they are often embedded in local knowledge and food traditions. Notably, many NUCs are managed and cultivated by women, making them central to intra-household food security and income generation. Improvements in the productivity and commercialization of these crops therefore have important implications for gender equity and resource allocation within households (Padulosi et al., 2013).

Furthermore, in the context of climate change, the concept of productivity itself must be reconsidered. A crop that produces moderate but stable yields under variable conditions may be more valuable in the long run than one that produces high yields under optimal conditions but fails under stress. In this sense, resilience can be viewed as a form of productivity, particularly in environments characterized by high uncertainty. NUCs, with their consistent performance under adverse conditions, may therefore represent a different but equally important pathway to agricultural productivity.

The key concepts and theoretical tools derived from the literature are utilised throughout this study and are summarised in the table below.

Table 1: Key Concepts and Their Relationship to the Study

Concept	Definition	Key Relationship to Study
Sustainable Agricultural Productivity (SAP)	Enhancing agricultural output value or quantity compared to inputs by optimizing efficiencies across the entire agri-food system while factoring in present and future environmental, economic, and social performance (USDA, 2023).	The goal, achieved by promoting the high TFP and environmental benefits of NUCs.
Total Factor Productivity (TFP)	An indicator of agricultural efficiency, measuring the output growth not directly attributed to input increases (Fuglie, 2018).	The primary dependent variable and measurement tool, quantifying resource-use efficiency and sustainability.
Relationship between SAP and TFP	SAP is enhanced when TFP increases, as higher TFP reflects more efficient and resource-conserving production that supports long-term sustainability (FAO, 2018).	Provides the theoretical justification for using TFP as the key metric for sustainability assessment.
DEA Malmquist Index	A non-parametric method assessing TFP change over time, decomposing it into Efficiency Change (Effch) and Technological Change (Techch) without pre-specifying the relationship between inputs and outputs (Coelli et al., 2005).	The core analytical methodology used to generate comparable TFP estimates for NUCs and SCs.
Sustainable Food Systems	Systems ensuring food security and nutrition while balancing economic viability, social equity, and environmental responsibility (FAO, 2018).	The broad policy outcome that NUC-based TFP growth is designed to achieve.

Source: Author's own compilation.

2.4 Synthesis and Implications for Productivity Assessment

The literature demonstrates that agricultural productivity is multidimensional and cannot always be adequately represented through yield-based measures alone. While staple crops remain central to food security and agricultural policy, their prominence in productivity analysis is closely associated with production systems characterised by comparatively intensive use of external inputs. NUCs, by contrast, are frequently cultivated under lower-input and more environmentally constrained conditions while providing additional benefits related to climate resilience, soil health, biodiversity, nutrition, and livelihoods.

These differences have important implications for comparative productivity assessment. Yield-based indicators capture the amount of output obtained from a particular input, most commonly land, but do not account simultaneously for the broader bundle of resources used in production. Consequently, comparisons based exclusively on yield may provide an incomplete representation of the relative performance of crop systems that differ substantially in their input requirements.

TFP provides a useful analytical framework for addressing this limitation because it evaluates output relative to multiple production inputs and allows changes in productivity to be examined through both efficiency change and technological change. This distinction is particularly relevant to the present study because Uganda and South Africa represent contrasting agricultural production environments, with differences in input intensity, technology adoption, and production structure.

Despite the recognised sustainability characteristics of NUCs, their inclusion in TFP-based agricultural productivity analysis remains limited. Existing research has concentrated predominantly on their agronomic, nutritional, and environmental attributes, while comparative evidence on their multi-factor productivity performance relative to staple crops

remains less developed. Data constraints and the limited representation of NUCs in official agricultural statistics have further restricted such assessments (Fuglie & Rada, 2013).

The reviewed literature therefore provides the basis for evaluating NUCs and staple crops through a productivity framework that accounts for differences in resource use rather than relying on output alone. The present study applies this perspective through a comparative DEA-Malmquist analysis of crop productivity in Uganda and South Africa, complemented by literature-based evidence on the sustainability characteristics of NUCs. The methodological approach used to operationalise this comparison is presented in the following section.

Chapter 3: Methodology

3.1 Research Design

This study employed a sequential mixed-methods research design that integrated qualitative evidence synthesis with quantitative productivity analysis to evaluate the comparative performance of neglected and underutilized crops and staple crops in Uganda and South Africa. The design was selected because the research sought to answer complementary questions concerning both the sustainability characteristics of NUCs and their economic productivity. Addressing these objectives required combining evidence from published literature with empirical estimates of agricultural productivity, thereby providing a more comprehensive assessment than either qualitative or quantitative methods could achieve independently.

The study was implemented in two interrelated phases. The first phase consisted of an Integrative Literature Review (ILR) that synthesized current empirical evidence regarding the sustainability contributions of NUCs. Rather than focusing solely on agronomic performance, the review examined multiple dimensions of sustainability, including climate resilience, soil health, resource-use efficiency, nutritional quality, biodiversity conservation, and livelihood outcomes. This qualitative synthesis established the conceptual foundation for interpreting subsequent productivity results by demonstrating why conventional yield-based comparisons may underestimate the broader value of NUCs within sustainable food systems.

The second phase comprised a TFP analysis using Data Envelopment Analysis and the Malmquist Productivity Index. This phase provided the principal empirical contribution of the study by estimating technical efficiency, technological change, and productivity growth across crop categories and countries. Unlike conventional productivity indicators based solely on yield or labour productivity, TFP incorporates multiple production inputs simultaneously, thereby providing a more comprehensive measure of agricultural performance. This approach was particularly appropriate because neglected crops are typically cultivated under lower-input production systems than conventional staple crops, making comparisons based solely on yield potentially misleading.

The sequential design ensured that findings from the literature review informed the interpretation of the quantitative analysis without influencing the estimation procedures themselves. Consequently, qualitative evidence explained the sustainability implications of observed productivity patterns, while the quantitative analysis provided objective measures of economic performance that could be compared across crop systems and national contexts. Integrating both strands of evidence enabled the study to evaluate NUCs not only as resilient crops but also as economically viable components of sustainable agricultural systems.

Table 2: Research Design and Analytical Procedures

Phase	Objective	Method	Data Source	Output
Phase I	Examine sustainability contributions of NUCs	Integrative Literature Review	Peer-reviewed literature, FAO, CGIAR, institutional publications	Evidence synthesis across sustainability dimensions
Phase II	Compare productivity between NUCs and staple crops	DEA–Malmquist TFP analysis	Harmonised panel dataset (2010–2022)	Technical efficiency, TFP, Effch and Techch
Validation	Test differences between crop categories and countries	Welch t-tests, ANOVA, descriptive statistics	DEA outputs and productivity indicators	Statistical validation
Robustness	Evaluate consistency of findings	CRS–VRS comparison and partial productivity indicators	DEA estimates	Sensitivity assessment

Source: Author's own compilation.

3.2 Analytical Framework

The analytical framework combines production economics with sustainability thinking to assess whether NUCs match conventional staples in productivity while also supporting broader sustainability goals, using land, labour, fertilizer, pesticides, mechanisation, and irrigation as inputs and yield per hectare as the harmonised output measure. DEA forms the core method, building a non-parametric production frontier to estimate technical efficiency without assuming a fixed functional form well suited to the heterogeneous technologies found across smallholder and commercial systems.

The Malmquist Productivity Index extends this by decomposing Total Factor Productivity growth into Efficiency Change (movement toward the frontier) and Technological Change (shifts in the frontier itself), allowing productivity gains in Uganda's smallholder-driven system to be distinguished from South Africa's more technology-driven gains.

These productivity estimates are then compared across crop categories and tested statistically to confirm whether differences are systematic, and finally interpreted alongside sustainability evidence, climate resilience, soil health, biodiversity, resource efficiency, and nutrition so productivity findings are read within a broader sustainable food systems perspective rather than purely economic terms.

3.3 Study Scope

The study compares agricultural productivity between NUCs and staples across Uganda and South Africa, two contrasting systems chosen for their differing institutional, technological, and agroecological conditions: Uganda's smallholder, rain-fed, low-input agriculture versus South Africa's mechanised, higher-input, commercial sector. This contrast allows the study to test whether productivity patterns hold across fundamentally different farming environments.

The analysis draws on a balanced panel spanning 2010–2022 (thirteen years), chosen for maximum data availability and consistency across national and international sources, meeting the consecutive-observation requirements of Malmquist productivity estimation. Seven crops common to both countries were included maize, rice, and beans as staples, and sorghum, finger millet, cowpea, and groundnut as NUCs selected for their regional importance and data

completeness. Each crop-country-year combination forms a single observation (decision-making unit) in the DEA and Malmquist analyses.

3.4 Phase I: Integrative Literature Review Protocol

The qualitative phase of the research employed an Integrative Literature Review to synthesise current knowledge regarding the sustainability contributions of neglected and underutilised crops. Unlike traditional narrative reviews, an integrative review allows evidence from diverse methodological traditions including quantitative, qualitative, mixed-methods, and institutional studies, to be combined into a coherent analytical synthesis. This approach was appropriate because evidence relating to NUCs spans agronomy, agricultural economics, ecology, nutrition, climate science, and rural development.

The purpose of the review was not to estimate effect sizes through statistical meta-analysis but rather to identify recurring patterns concerning the contribution of NUCs to sustainable agricultural systems. Specifically, the review sought evidence relating to climate resilience, soil health, biodiversity conservation, resource-use efficiency, nutritional quality, and livelihood outcomes. These themes subsequently provided the conceptual context within which empirical productivity findings were interpreted.

The review followed a structured and transparent protocol consisting of five stages: literature identification, screening, eligibility assessment, quality appraisal, and thematic synthesis. Although the review was not conducted as a formal systematic review, its procedures were informed by PRISMA principles to enhance transparency and reproducibility.

3.4.1 Literature Search Strategy

A comprehensive search was undertaken across major bibliographic databases and institutional repositories. Primary databases included Scopus, CAB Abstracts, and Google Scholar, while supplementary evidence was obtained from FAO, CGIAR, HarvestPlus, the World Bank, IFPRI, and national agricultural research organisations.

For searching purposes, the following strings were applied: ("Neglected and Underutilized Crops" OR "Orphan crops" OR "Indigenous crops") AND ("Productivity" OR "Total Factor Productivity" OR "Sustainability" OR "Climate Resilience" OR "Crop Diversification" OR "DEA" OR "Malmquist") AND ("Uganda" OR "South Africa" OR "Sub-Saharan Africa"). The range of the publications searched is between 2010 and 2025, reflecting the rapidly expanding literature on climate-smart agriculture, sustainable intensification, and neglected crops. All the references from the database and grey literature searching process were imported to Zotero reference management software, where they were organised and screened for duplicates.

3.4.2 Inclusion and Exclusion Criteria

Studies were included where they:

- examined neglected and underutilised crops or staple crops within Sub-Saharan Africa;
- addressed sustainability, productivity, resilience, nutrition, or resource efficiency;
- reported empirical evidence;
- were published in peer-reviewed journals or reputable institutional reports;

- were written in English.

Studies were excluded where they:

- lacked empirical evidence;
- focused exclusively on laboratory or genetic research unrelated to agricultural production;
- addressed regions outside the study context without transferable findings;
- duplicated previously identified publications;
- provided insufficient methodological detail.

Following screening and eligibility assessment, 38 studies satisfied all inclusion criteria and formed the evidence base for qualitative synthesis.

3.4.3 Quality Appraisal and Evidence Synthesis

Each retained publication underwent critical appraisal to evaluate methodological transparency, analytical rigour, relevance to the research objectives, and applicability to Sub-Saharan African agricultural systems. Rather than assigning numerical quality scores, appraisal focused on whether studies clearly described research design, sampling procedures, analytical methods, and principal findings.

Relevant information was extracted into structured evidence matrices recording study location, crop species, methodological approach, sustainability dimensions investigated, and principal conclusions. Extracted findings were subsequently coded using thematic analysis.

Themes were developed iteratively as evidence accumulated, ultimately converging around six principal sustainability dimensions: climate resilience, soil health and ecosystem services, resource-use efficiency, food and nutrition security, livelihood and socio-economic outcomes, and agricultural diversification and system resilience.

The final synthesis adopted a narrative-convergent approach in which findings from diverse study designs were integrated into coherent thematic interpretations. These themes established the conceptual foundation for interpreting the quantitative DEA–Malmquist productivity results presented in subsequent chapters.

3.5 Phase II: Quantitative Research Design Overview

The quantitative component of this study was based on a harmonised balanced panel dataset constructed from internationally recognised agricultural databases and official national statistical sources. The objective of the compilation process was to develop a consistent dataset suitable for estimating TFP using Data Envelopment Analysis and the Malmquist Productivity Index. Because the analysis compared productivity across countries, crop categories, and time, particular emphasis was placed on ensuring comparability of variables, temporal consistency, and completeness of observations.

3.5.1 Data Sources

The study utilised secondary data compiled from internationally recognised statistical databases and official national statistical agencies to ensure consistency, reliability, and comparability.

The principal source of agricultural production statistics was FAOSTAT, which provides internationally harmonised information on crop production, harvested area, yields, and agricultural inputs. FAOSTAT was selected because of its standardised reporting procedures and extensive country coverage, making it particularly suitable for cross-country productivity comparisons.

National statistics obtained from the Uganda Bureau of Statistics (UBOS) and Statistics South Africa (Stats SA) complemented FAOSTAT by providing additional agricultural indicators and facilitating validation of production estimates where necessary. National datasets were especially valuable for confirming trends in crop production and ensuring consistency between internationally reported statistics and official domestic records. Using multiple complementary data sources enhanced the reliability of quantitative analyses while reducing dependence on a single information source.

3.5.2 Data Compilation

Data were compiled for the period 2010–2022, providing thirteen consecutive years of observations. This period was selected because it represented the longest interval over which comparable information was available for all selected crops and production variables across Uganda and South Africa. Restricting the analysis to a common period minimised temporal inconsistencies while satisfying the sequential data requirements of Malmquist productivity estimation.

The empirical dataset comprised seven crop species selected on the basis of agronomic relevance, nutritional importance, and data availability. Three crops represented conventional staples (maize, rice, and beans), while four represented neglected and underutilised crops (finger millet, sorghum, cowpea, and groundnut). These crops occur in both countries and collectively capture a broad spectrum of production systems, ranging from high-input commercial agriculture to predominantly low-input smallholder farming.

Following compilation, individual datasets were merged using common identifiers for country, crop, and year. Variable names, coding structures, and measurement units were standardised before statistical analysis. Duplicate observations were removed, variables were screened for inconsistencies, and missing observations were examined prior to harmonisation. Only observations satisfying predefined completeness requirements were retained for productivity estimation.

3.5.3 Variable Definition

Variable selection was guided by production theory, prior TFP studies, and data availability across both countries, aiming to capture the main factors in crop production without redundancy among inputs. Output was measured as crop yield (kg/ha) rather than value of production, since consistent price data weren't available across all crops and years, yield offers a reliable physical measure widely used in comparative productivity studies.

The input set covered the major production resources: harvested area (land), labour, fertiliser use, pesticide use, irrigation expenditure, and mechanisation costs. Together these variables represent the multidimensional nature of agricultural production, allowing productivity to be assessed as the joint transformation of several inputs into output rather than through a single-factor measure.

Beyond these observed variables, DEA generated technical efficiency scores for each decision-making unit, and the Malmquist Index derived Total Factor Productivity Change (TFPCH) along with its two components, Efficiency Change (Effch) and Technological Change (Techch) which served as the main dependent measures in the comparative analysis.

Table 3: Operational Definition of Variables

Variable	Operational Definition	Unit	Role
Harvested area	Total cultivated area allocated to each crop	Hectares	Input
Labour	Agricultural labour employed during production	Persons or labour equivalent	Input
Fertiliser	Quantity of mineral fertiliser applied	kg nutrient equivalent	Input
Pesticides	Quantity of crop protection chemicals applied	kg active ingredient	Input
Irrigation	Cost associated with irrigation activities	Constant USD	Input
Mechanisation	Machinery and equipment expenditure	Constant USD	Input
Yield	Crop production per harvested hectare	kg ha ⁻¹	Output
DEA efficiency	Relative technical efficiency score	Index	Derived
Efficiency Change	Movement towards production frontier	MPI component	Derived
Technological Change	Shift of production frontier	MPI component	Derived
Total Factor Productivity	Overall productivity change	MPI index	Derived

Source: Author's own compilation.

3.5.4 Data Harmonisation

Combining agricultural data from multiple national and international sources required extensive harmonisation before productivity estimation, ensuring that observed productivity differences reflected genuine performance variation rather than inconsistencies in data collection, units, or reporting. This involved four sequential stages: unit standardisation, temporal alignment, treatment of missing data, and consistency verification.

Units were standardised across all variables, land in hectares, output in kg/ha, fertiliser and pesticide in nutrient/active-ingredient equivalents, and monetary variables in constant USD to remove inflation effects. Observations were then aligned to calendar years within 2010–2022, with records outside this window excluded and reporting-calendar mismatches reconciled. Missing values were interpolated where gaps were isolated within otherwise complete series, while variables with extensive or systematic gaps were dropped to avoid bias.

Finally, descriptive statistics, graphical inspection, and frequency checks were used to catch outliers, duplicates, and coding errors before correction or exclusion. The result was a balanced panel with consistent definitions and complete observations across all units critical for DEA, which is sensitive to measurement error, and essential to the robustness of the productivity estimates.

3.5.5 Partial Productivity Indicators

Although TFP provides the most comprehensive productivity measure, partial productivity indicators were estimated to complement DEA results and facilitate interpretation of resource-use efficiency.

The following indicators were calculated:

Land productivity

$$LP = \frac{\text{output}}{\text{Land}}$$

Labour productivity

$$LabP = \frac{\text{Output}}{\text{Labour}}$$

Fertiliser productivity

$$FP = \frac{\text{Output}}{\text{Fertiliser}}$$

Pesticide productivity

$$PP = \frac{\text{Output}}{\text{Pesticides}}$$

Mechanisation productivity

$$MP = \frac{\text{Output}}{\text{Mechanisation}}$$

These indicators were not interpreted as substitutes for TFP but rather as descriptive measures illustrating how efficiently individual production factors contributed to agricultural output. Comparing partial productivity with DEA results also provided additional evidence regarding the resource-use characteristics of NUCs relative to staple crops.

3.5.6 Data Envelopment Analysis (DEA)

DEA is a non-parametric frontier technique developed by Charnes, Cooper and Rhodes (1978) and extended by Banker, Charnes and Cooper (1984) to accommodate Variable Returns to Scale. Rather than assuming a functional form, it builds an empirical production frontier directly from observed data, identifying the best-performing units as the efficient benchmark.

DEA was chosen for three reasons. First, it evaluates the joint use of land, labour, fertiliser, pesticides, irrigation, and mechanisation, overcoming the single-input limitation of partial productivity measures like yield or labour productivity. Second, its non-parametric nature accommodates the heterogeneous agroecological conditions, technologies, and farm structures across Uganda and South Africa without imposing a common production technology.

Thirdly, DEA underpins the Malmquist Productivity Index, which relies on DEA-derived distance functions to measure productivity change over time ensuring methodological consistency between efficiency estimation and productivity decomposition.

3.5.7 Decision-Making Units (DMUs)

In this study, each DMU represented a unique combination of country, crop, and production year. Thus, observations such as Uganda–Finger Millet–2014 and South Africa–Maize–2018 constituted individual production units evaluated relative to all other observations within the sample.

Defining DMUs in this manner offered several methodological advantages. It preserved the temporal dimension required for Malmquist productivity estimation, allowed direct comparison between crop categories within countries, and enabled productivity trajectories to be monitored throughout the study period. Treating each crop-year observation independently also avoided aggregation bias that could obscure variation among crop species or production systems.

3.5.8 Malmquist Productivity Index (MPI)

To evaluate dynamic productivity performance, this study employed the Malmquist Productivity Index. The Malmquist framework measures changes in Total Factor Productivity between consecutive time periods using DEA-based distance functions.

The output-oriented Malmquist index between periods t and $t + 1$ is expressed as:

$$MPI = \left[\frac{D_t(x_{t+1}, y_{t+1})}{D_t(x_t, y_t)} \times \frac{D_{t+1}(x_{t+1}, y_{t+1})}{D_{t+1}(x_t, y_t)} \right]^{1/2}$$

where $D(\cdot)$ denotes output distance functions estimated using DEA.

Values of the Malmquist index are interpreted as follows:

- $MPI > 1$: productivity improvement;
- $MPI = 1$: no productivity change;
- $MPI < 1$: productivity decline.

The principal strength of the Malmquist approach lies in its decomposition of overall productivity into two conceptually distinct components:

$$MPI = Effch \times Techch$$

where:

$$Effch = \frac{D_{t+1}(x_{t+1}, y_{t+1})}{D_t(x_t, y_t)}$$

measures movement towards the existing production frontier, and

$$Techch = \left[\frac{D_t(x_{t+1}, y_{t+1})}{D_{t+1}(x_{t+1}, y_{t+1})} \times \frac{D_t(x_t, y_t)}{D_{t+1}(x_t, y_t)} \right]^{1/2}$$

measures shift in the production frontier resulting from technological progress.

This decomposition was central to the objectives of the study because it distinguished productivity improvements arising from better management practices from those attributable to technological innovation.

3.5.9 Statistical Validation

To evaluate whether productivity differences between crop categories and countries were statistically significant, inferential analyses were undertaken.

Because preliminary diagnostics indicated unequal variances among several productivity indicators, Welch's two-sample t-test was used in preference to the classical Student's t-test. Welch's procedure provides more reliable inference when group variances differ, and sample sizes are unequal.

For comparisons involving more than two groups, Analysis of Variance (ANOVA) was employed to evaluate whether observed differences in productivity measures exceeded those expected through sampling variation alone. Where ANOVA indicated significant differences, appropriate post hoc comparisons were conducted to identify specific group contrasts.

Statistical significance was evaluated using the conventional thresholds of $p < 0.05$, $p < 0.01$, and $p < 0.001$. These inferential procedures complemented DEA by determining whether observed productivity patterns represented statistically meaningful differences.

Chapter 4: Results and Discussion

This chapter presents and discusses the findings of the study in relation to the research objectives and analytical framework. Drawing on both the integrative literature review and the quantitative TFP analysis, the chapter provides a comparative assessment of NUCs and staple crops in Uganda and South Africa. The integration of qualitative and quantitative evidence enables a broader understanding of the sustainability and productivity dimensions associated with different crop systems.

The chapter is organized into two interrelated phases. The first phase synthesizes evidence from the integrative literature review, focusing on the sustainability contributions of NUCs across key themes including climate resilience, soil health, resource efficiency, nutrition, and livelihood support. This section establishes the conceptual foundation for understanding the broader role of NUCs within agricultural systems and highlights the key gaps that motivate the empirical analysis.

The second phase presents the results of the quantitative analysis based on the DEA–Malmquist framework. This includes estimates of technical efficiency, Total Factor Productivity, and the decomposition of productivity change into efficiency change and technological change components. Comparative analyses are undertaken across crop categories and countries in order to examine patterns of productivity and resource use efficiency under different production conditions.

Rather than treating sustainability and productivity as separate dimensions, the chapter adopts an integrated analytical perspective that considers how resource use, efficiency, and technological dynamics interact to shape agricultural performance. In doing so, the analysis moves beyond conventional yield-based comparisons and evaluates whether NUCs can achieve competitive productivity outcomes when assessed using a multi-factor productivity framework.

The discussion further situates the findings within the broader literature on agricultural diversification, sustainable intensification, and food system resilience in Sub-Saharan Africa. Particular attention is given to how variations in productivity dynamics across crop systems may inform debates on sustainability, input use efficiency, and the role of diversified agricultural systems in addressing emerging food system challenges.

4.1 Sustainability Contributions of Neglected and Underutilized Crops

The integrative literature review demonstrates that neglected and underutilized crops make substantial contributions to the sustainability of agricultural systems across Sub-Saharan Africa. Across the 38 studies included in the review, NUCs consistently emerged as multifunctional crops that support environmental sustainability, climate adaptation, efficient resource utilization, improved nutrition, and resilient rural livelihoods.

Although the magnitude of these contributions varied across agroecological settings and crop species, there was broad agreement that NUCs possess characteristics that make them particularly valuable for addressing the intertwined challenges of climate change, land degradation, declining agricultural productivity, and food insecurity. To facilitate a systematic

discussion, the findings are organized around four interrelated sustainability dimensions: climate resilience and adaptation; soil health and ecosystem services; resource efficiency and sustainable production; and nutrition, food security, and livelihoods.

4.1.1 Climate Resilience and Adaptation

Of the 38 studies included in the integrative literature review, the overwhelming majority identified climate resilience as one of the defining characteristics of neglected and underutilized crops. Sorghum, finger millet, cowpea and groundnut emerged most consistently across studies conducted in Uganda, South Africa and other parts of Sub-Saharan Africa as crops capable of maintaining production under drought, high temperatures and erratic rainfall. Several studies further reported that these crops exhibit adaptive traits such as deep rooting systems, shorter growing cycles, efficient water use, and greater tolerance to poor soils, enabling them to sustain production where conventional staple crops frequently fail.

These findings are consistent with a broader body of literature that increasingly recognizes NUCs as strategic components of climate-resilient agriculture. Chivenge et al. (2015), Mabhaudhi et al. (2019), Tadele (2019), Padulosi et al. (2013), Jamnadass et al. (2020) and Mabhaudhi et al. (2017), among others, argue that the resilience of NUCs extends beyond simple drought tolerance. Their adaptability results from a combination of physiological, genetic and ecological characteristics that enable stable production under increasingly variable climatic conditions. Likewise, Lin (2011) and Altieri et al. (2015) emphasize that crop diversification through resilient species enhances the adaptive capacity of farming systems while reducing production risks associated with climate variability.

In contrast, highly input-dependent staple crops such as maize frequently experience substantial yield losses during prolonged droughts, particularly within rain-fed production systems that dominate much of Sub-Saharan Africa (Lobell et al., 2011; Cairns et al., 2013). These vulnerabilities are further exacerbated in smallholder systems where access to irrigation infrastructure, improved seed varieties, crop insurance and climate-smart technologies remains limited (Morton, 2007; Cooper et al., 2008). Consequently, the literature increasingly positions NUCs not as supplementary crops but as strategic assets for strengthening climate adaptation, stabilizing agricultural production and reducing climate-related risks.

Collectively, these findings suggest that resilience should be viewed as an important dimension of agricultural productivity rather than merely an ecological characteristic. A crop capable of producing moderate but stable yields across variable climatic conditions may contribute more effectively to long-term food system resilience than a crop capable of exceptionally high yields only under favourable conditions. While the literature convincingly establishes the adaptive advantages of NUCs, relatively little is known about whether these resilience characteristics are accompanied by competitive economic productivity. This gap provides an important justification for the quantitative Total Factor Productivity analysis undertaken in the second phase of this study.

Table 4: Comparative Resilience and Sustainability Attributes of NUCs and Staple Crops

Nutrient Attribute	NUCs (Amaranth, Cowpea, Bambara groundnut)	Staple Crops (Maize, Wheat, Rice)	Relative Advantage
Drought tolerance	High – physiological and genetic adaptation to moisture stress	Moderate to low	NUCs perform better under water stress
Water-use efficiency	1.2–1.8 kg grain/m ³ water (Uganda, SA average)	0.6–0.9 kg grain/m ³ water	NUCs 40–60% more efficient
Input requirements	Minimal fertilizer and pesticide needs	High dependence on synthetic inputs	NUCs more sustainable and cost-effective
Temperature resilience	Yield stability up to 35–38°C	Sharp decline beyond 30°C	NUCs outperform staples in heat tolerance
Biodiversity contribution	Promotes intercropping, agro-biodiversity, pest suppression	Reduces diversity in monocultures	NUCs enhance ecosystem stability

Source: Author's own compilation.

4.1.2 Soil Health and Ecosystem Services

The integrative review also demonstrates strong evidence that NUCs contribute significantly to soil restoration and ecosystem functioning. Most of the reviewed studies reported that leguminous crops such as cowpea and groundnut improve soil fertility through biological nitrogen fixation, while cereals such as sorghum and millet contribute to maintaining soil cover and reducing erosion. Several studies further documented improvements in soil organic matter, enhanced microbial activity and greater moisture retention when NUCs were incorporated into diversified cropping systems.

These observations align closely with findings reported by Snapp et al. (2010), Giller et al. (2021), Pretty et al. (2018), Lal (2020), Chivenge et al. (2015) and the FAO (2021), who argue that NUCs deliver valuable ecosystem services extending well beyond food production. Their inclusion in crop rotations and intercropping systems has been shown to improve nutrient cycling, interrupt pest and disease cycles, enhance biodiversity and increase the ecological stability of farming systems. Such services are particularly valuable in low-input production environments where declining soil fertility and ecosystem degradation remain persistent constraints to sustainable agricultural production.

From a broader sustainability perspective, these findings indicate that the contribution of NUCs should not be evaluated solely through marketable outputs. Rather, they generate environmental benefits that strengthen the long-term productive capacity of agricultural systems. Nevertheless, these ecosystem services are rarely incorporated into conventional productivity assessments, which typically emphasize crop yields or gross output while overlooking improvements in natural capital. Consequently, an important question remains as to whether these ecological advantages are reflected in measurable improvements in production efficiency when multiple inputs and outputs are considered simultaneously.

4.1.3 Resource Efficiency and Sustainable Production

Resource efficiency emerged as another dominant theme across the reviewed literature. A large proportion of the reviewed studies reported that NUCs consistently achieve acceptable levels of production while requiring substantially lower quantities of fertilizer, irrigation water, pesticides and mechanization than conventional staple crops. This characteristic was particularly evident under resource-constrained conditions where farmers faced limited access to purchased inputs.

The broader literature strongly supports these findings. Fuglie (2015), Coelli and Rao (2005), Pretty et al. (2018), Tilman et al. (2017), Lin (2011) and Mabhaudhi et al. (2019) collectively argue that sustainable agricultural systems should increasingly be evaluated according to how efficiently they transform available resources into outputs rather than simply maximizing yields through greater input intensification. In this context, resource-use efficiency represents a critical component of sustainable intensification, particularly in developing countries where agricultural growth must occur under increasing resource scarcity.

The evidence suggests that lower dependence on external inputs provides several complementary advantages. Reduced production costs improve farm profitability, lower exposure to volatile input markets and reduce environmental pressures associated with excessive fertilizer and agrochemical use. However, much of the existing evidence remains based on partial productivity indicators or agronomic experiments rather than comprehensive assessments of overall production efficiency.

This distinction is particularly important because high yields do not necessarily imply superior productivity if they are achieved through disproportionately greater input use. Evaluating whether the apparent resource efficiency of NUCs translates into higher overall productivity therefore requires a Total Factor Productivity framework capable of jointly considering multiple inputs and outputs.

4.1.4 Nutrition, Food Security and Livelihoods

The review further demonstrates that NUCs contribute substantially to nutrition security, household resilience and rural livelihoods. Nearly all studies examining nutritional outcomes reported that NUCs possess superior concentrations of essential micronutrients, dietary fibre, proteins and bioactive compounds compared with many dominant staple crops. Finger millet, for example, consistently emerged as an important source of calcium and iron, while cowpea provides high-quality plant protein and several essential amino acids.

These findings are widely supported within the literature. Mabhaudhi et al. (2017), Padulosi et al. (2013), Jamnadass et al. (2020), Chivenge et al. (2015), Tadele (2019), FAO (2023) collectively emphasize that NUCs contribute simultaneously to dietary diversity, improved micronutrient intake and enhanced household food security. Their relatively long storage life further strengthens household resilience during periods of climatic or economic shocks by ensuring more stable food availability throughout the year.

Beyond nutritional outcomes, several studies highlighted the broader socioeconomic significance of NUCs. These crops remain closely associated with indigenous knowledge systems, cultural identity and informal seed networks, while women frequently play central roles in their production, processing and marketing (Padulosi et al., 2013; Mabhaudhi et al., 2019). Consequently, increasing the productivity and commercialization of NUCs has implications extending beyond agriculture to encompass gender equity, livelihood diversification and inclusive rural development.

Despite this growing body of evidence, the economic contribution of NUCs remains insufficiently quantified. Most studies assess nutritional or livelihood benefits independently of production efficiency, leaving unanswered the question of whether these wider sustainability contributions are accompanied by competitive economic performance relative to staple crops.

Table 5: Comparative Nutrient Composition of NUCs and Staple Crops

Nutrient Attribute	NUCs (Amaranth, Cowpea, Bambara groundnut)	Staple Crops (Maize, Wheat, Rice)	Relative Advantage	Key References
Protein content (%)	18–23	8–11	+100% higher	Munialo et al. (2024), Veldsman et al. (2023)
Iron (mg/100g)	6–9	1–3	2–3× higher	Bua & Onang (2017), Munialo et al. (2024)
Calcium (mg/100g)	250–400	20–40	10× higher	Bua & Onang (2017), Munialo et al. (2024), Veldsman et al. (2023)
Dietary fibre (g/100g)	8–11	2–4	3× higher	Bua & Onang (2017), Munialo et al. (2024), Veldsman et al. (2023)
Glycaemic index	35–45	65–75	Lower (healthier)	Mabhaudhi et al. (2017), Munialo et al. (2024), Ndiovu et al. (2024)

Source: Author's own compilation.

4.1.5 Synthesis and Implications for the Quantitative Analysis

Taken together, the integrative literature review presents compelling evidence that NUCs contribute to agricultural sustainability through multiple, mutually reinforcing pathways. Across the reviewed studies, there is broad consensus that these crops enhance climate resilience, improve soil health, utilize resources more efficiently and strengthen household nutrition and livelihoods. Collectively, these attributes position NUCs as important components of diversified and sustainable food systems.

However, a critical gap persists within the existing literature. Most studies evaluate NUCs from ecological, agronomic or nutritional perspectives, while comparatively few assess their performance using comprehensive measures of economic productivity. Furthermore, where productivity is examined, analyses are commonly based on yield or partial productivity indicators that fail to account for differences in input use intensity and production efficiency.

This limitation provides the principal motivation for the quantitative analysis in Phase II of this study. Building upon the sustainability evidence established through the integrative literature review, the subsequent analysis applies a Total Factor Productivity framework to determine whether the ecological and social advantages of NUCs are accompanied by comparable or superior economic performance relative to staple crops under contrasting production systems in Uganda and South Africa.

4.2 Comparative Productivity Performance

Building on the sustainability evidence presented in the preceding section, this section turns to the empirical core of the study: a comparative assessment of productivity performance between neglected and underutilised crops and staple crops in Uganda and South Africa. The analysis proceeds in stages, beginning with the production environments in which these crops are cultivated and closing with a formal TFP decomposition using Data Envelopment Analysis and the Malmquist Productivity Index.

Unlike yield or other single-factor indicators, TFP evaluates production performance as the joint transformation of multiple inputs, land, labour, fertiliser, pesticides, irrigation, and mechanisation, into agricultural output. Decomposing the Malmquist Index into efficiency change and technological change further isolates whether productivity growth stems from better resource management or from genuine technological progress, a distinction that proves central to interpreting the contrasting trajectories of the two study countries.

The results are presented in a logical sequence: descriptive statistics establish the production context; partial productivity ratios offer an initial, single-input view of performance; DEA then estimates static technical efficiency; and the Malmquist decomposition captures productivity change over time. The section closes with a set of robustness checks, panel regression, variance decomposition, and policy simulation, that test whether these patterns hold under alternative analytical approaches.

4.2.1 Production Environments and Input Intensity

Table 6 summarises input use and yield for Uganda and South Africa. South Africa consistently applies more fertiliser, pesticide, irrigation, and mechanisation than Uganda, while Uganda relies far more heavily on labour (mean 78.8 versus 20.7 person-days per hectare). This contrast is not incidental: it marks two structurally distinct productivity pathways. South Africa's capital-intensive system is positioned to benefit from technological progress, while Uganda's labour-intensive, low-input system depends more on how efficiently existing resources are allocated.

Table 6: Summary statistics of agricultural input use and yield in Uganda and South Africa

Variable	Country	Obs	Mean	Median	SD	Min	Max
Fertilizer use (kg/ha)	Ug	91	0.240	0.168	0.208	0.052	0.875
	ZA	91	93.584	29.920	168.058	0.510	586.500
Pesticide use (kg/ha)	Ug	91	0.045	0.028	0.046	0.002	0.175
	ZA	91	2.383	0.088	5.728	0.020	17.500
Labor use (person-days/ha)	Ug	91	78.758	73.000	28.342	44.000	151.000
	ZA	91	20.681	19.000	7.784	11.000	40.000
Irrigation cost (USD/ha)	Ug	91	2.752	0.660	5.303	0.050	22.000
	ZA	91	10.283	7.220	10.113	0.510	44.400
Mechanisation cost (USD/ha)	Ug	91	3.981	2.530	3.475	0.770	12.790
	ZA	91	78.044	81.550	39.697	19.120	176.700
Yield (kg/ha)	Ug	91	1266.300	1244.300	646.148	386.400	2599.700
	ZA	91	1974.950	1382.300	1552.300	434.800	5921.100

Source: Author's calculations based on panel data.

Note: Ug = Uganda; ZA = South Africa.

A sharper distinction emerges when input use is examined by crop category rather than country (Table 7). Staple crops apply markedly more fertiliser, pesticide, irrigation, and mechanisation than NUCs across both countries, confirming that the two crop groups are not produced under comparable input regimes. NUCs cluster toward the lower end of the input spectrum, illustrated in Figure 3, yet do not correspondingly cluster at the lower end of productivity, a pattern that becomes central to interpreting the TFP results that follow.

Table 7: Summary Statistics of Agricultural Input Use and Yield in NUCs and Staple Crops

Crop Group	Variable	Obs	Mean	Median	SD	Min	Max
NUCs	Fertilizer use (kg/ha)	78	0.240	0.168	0.208	0.052	0.875
	Pesticide use (kg/ha)	78	0.045	0.028	0.046	0.002	0.175
	Labor use (person-days/ha)	78	78.758	73.000	28.342	44.000	151.000
	Irrigation cost (USD/ha)	78	2.752	0.660	5.303	0.050	22.000
	Mechanisation cost (USD/ha)	78	3.981	2.530	3.475	0.770	12.790
	Yield (kg/ha)	78	1266.300	1244.300	646.148	386.400	2599.700
SCs	Fertilizer use (kg/ha)	104	93.584	29.920	168.058	0.510	586.500
	Pesticide use (kg/ha)	104	2.383	0.088	5.728	0.020	17.500
	Labor use (person-days/ha)	104	20.681	19.000	7.784	11.000	40.000
	Irrigation cost (USD/ha)	104	10.283	7.220	10.113	0.510	44.400
	Mechanisation cost (USD/ha)	104	78.044	81.550	39.697	19.120	176.700
	Yield (kg/ha)	104	1974.950	1382.300	1552.300	434.800	5921.100

Source: Author's calculations based on panel data.

Staple crops consistently record higher absolute input use across both countries, particularly in fertilizer, mechanization, and irrigation. NUCs, on the other hand, are produced under low-input conditions, with significantly lower fertilizer and capital use. This pattern is visually reinforced in Figure 3, which shows NUCs clustered at the lower end of the input spectrum while staples occupy the higher end. This matters because it demonstrates that NUCs are structurally disadvantaged in conventional yield-based comparisons, yet they maintain stable yields and strong partial productivity ratios. Their ability to convert limited inputs into output efficiently becomes central when interpreting Total Factor Productivity results.

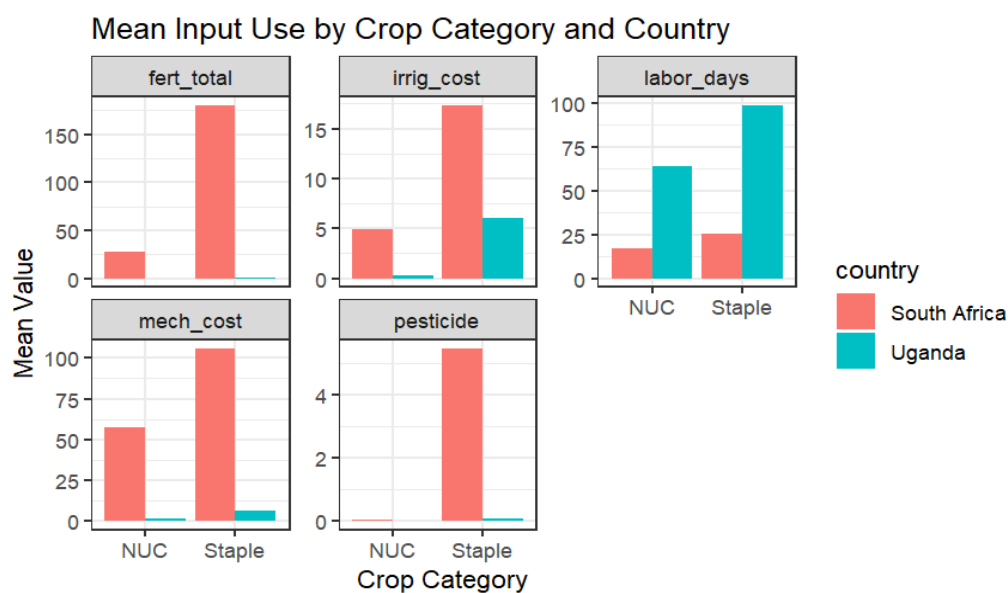


Figure 3: Comparative input intensity between neglected and staple crops in Uganda and South Africa
Source: Author's computation (2025)

Table 8: Crop-Level Descriptive Statistics for Uganda and South Africa

Uganda						
Crop (SC & NUC)	Fertilizer (kg/ha)	Pesticide (kg/ha)	Labor (person-days/ha)	Irrigation (USD/ha)	Mechanisation (USD/ha)	Yield (kg/ha)
Maize (SC)	0.6892	0.1231	85.23	2.035	10.436	2133.22
Rice (SC)	0.2954	0.0738	138.30	14.926	7.59	1882.30
Beans (SC)	0.1575	0.0390	72.50	1.080	10.846	1337.07
Sorghum (NUC)	0.0985	0.0197	59.69	0.2377	22.131	991.30
Millet (NUC)	0.0868	0.0144	51.15	0.1354	1.140	1404.95
Cowpea (NUC)	0.1198	0.0102	56.20	0.1008	11.392	479.90
Groundnut (NUC)	0.2363	0.0345	88.15	0.7462	28.162	635.28
South Africa						
Crop (SC & NUC)	Fertilizer (kg/ha)	Pesticide (kg/ha)	Labor (person-days/ha)	Irrigation (USD/ha)	Mechanisation (USD/ha)	Yield (kg/ha)
Maize (SC)	495.778	16.288	17.307	29.510	1332.177	4841.03
Rice (SC)	13.220	0.0765	37.07	7.310	105.170	2738.06
Beans (SC)	330.519	0.0931	21.46	15.286	79.464	1237.87
Sorghum (NUC)	33.050	0.1163	12.63	4.984	84.130	2855.646
Millet (NUC)	0.661	0.0233	13.92	0.996	29.214	490.82
Cowpea (NUC)	26.440	0.0238	12.00	1.596	26.292	437.35
Groundnut (NUC)	52.880	0.0930	23.53	12.296	88.810	1223.80

Source: Author's calculations based on panel data.

Crop-level descriptive statistics deepen this understanding. Maize and rice consistently record the highest yields, reflecting their intensive input use and improved varieties. Sorghum and finger millet exhibit stable yields across years, even under adverse conditions, while cowpea and groundnut show moderate but consistent yields, particularly in Uganda. These yield patterns are illustrated in Figure 4, which shows that staples outperform NUCs in absolute yield terms in both countries. However, this advantage is closely tied to their higher input intensity. In Uganda, yield gaps are narrower because all crops operate under low-input conditions; in South Africa, yield gaps widen due to the substantial input advantage enjoyed by staples. These observations highlight the limitations of yield-based comparisons and reinforce the need for multi-input productivity measures.

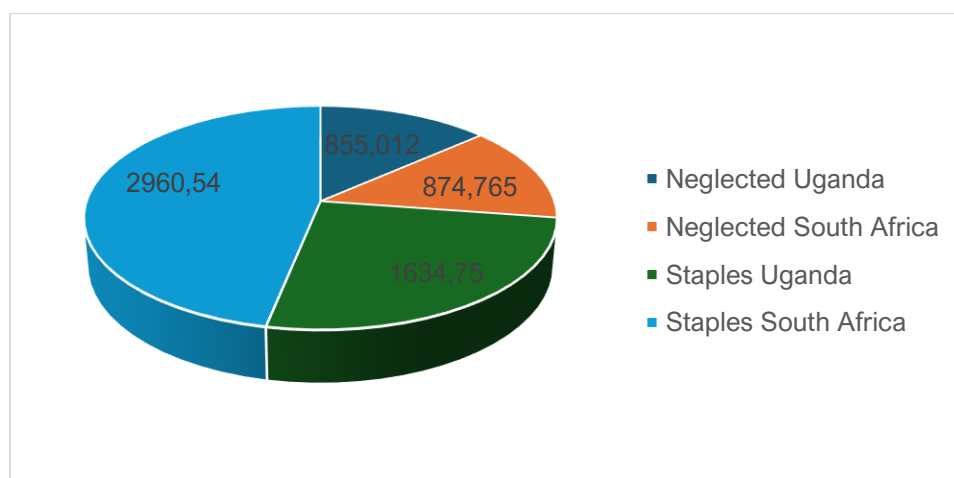


Figure 4: Mean yield (kg/ha) by crop category and country

Source: Author's calculations based on panel data.

4.2.2 Partial Productivity Analysis

Partial productivity ratios give a more detailed picture of how efficiently resources are used. To examine these patterns, Tables 9 and 10, present land, labour, fertilizer, irrigation, and mechanization productivity for each crop category and country.

Table 9: Partial Productivity by Crop Category and Country

Country	Crop Category	Fertilizer Productivity	Labor Productivity	Irrigation Productivity	Mechanization Productivity
ZA	Neglected	250.23	48.33	323.34	17.64
	Staple	86.07	142.58	319.79	28.84
Uganda	Neglected	8796.47	14.52	5640.35	629.09
	Staple	7008.97	18.64	1719.90	373.47

Source: Author's calculations based on panel data.

Table 10: Crop-Level Partial Productivity

Country	Crop	Fertilizer Productivity	Labor Productivity	Irrigation Productivity	Mechanization Productivity
SA	Beans	38.16	57.89	89.57	16.20
	Cowpeas	16.92	36.55	301.52	17.28
	Finger millet	759.60	35.37	541.99	17.46
	Groundnuts	23.73	52.19	107.35	14.26
	Maize	9.14	266.95	172.40	35.56
	Rice	210.71	74.07	413.53	26.99
	Sorghum	86.43	148.43	617.50	35.05
Uganda	Beans	9126.46	18.33	1435.05	564.44
	Cowpeas	4258.92	8.57	5271.40	438.42
	Finger millet	17611.72	27.63	11396.30	1278.22
	Groundnuts	2908.78	7.18	953.10	237.43
	Maize	3338.65	24.99	1147.96	212.30
	Rice	7099.74	13.42	138.47	259.66
	Sorghum	10631.12	16.73	4664.61	469.32

Source: Author's calculations based on panel data.

These tables show that land productivity is consistently higher for NUCs in Uganda, reflecting their adaptation to marginal soils and low-input environments. Finger millet and sorghum, in particular, generate more output per hectare than maize and rice under Uganda's smallholder conditions. This pattern indicates that NUCs are able to sustain production even where soil fertility is low, a characteristic that becomes important when interpreting efficiency scores.

Labour productivity is comparable across crop categories in both countries. Although staples generally receive more labour attention due to their commercial importance, NUCs achieve similar output per labour unit. This suggests that NUCs do not impose additional labour burdens on farmers and that their lower input intensity does not translate into lower labour efficiency. This observation challenges the perception that NUCs are "labour-heavy" crops and instead positions them as viable alternatives within labour-constrained smallholder systems.

The statistical comparison of inputs and yields confirms these descriptive patterns. Welch t-tests show large and statistically significant differences in fertilizer use, mechanization, and irrigation between Uganda and South Africa. Yield differences are also statistically significant, reflecting the structural advantages enjoyed by staples in South Africa. These statistical results validate the descriptive evidence and confirm that the observed differences are systematic rather than random.

Fertilizer productivity emerges as the most striking result. Even with minimal fertilizer application, crops such as sorghum and cowpea generate meaningful output, whereas maize and rice require significantly higher fertilizer quantities to achieve their yield levels. This pattern is visually reinforced in Figure 5, which provides a heatmap of partial productivity ratios across crops and countries. The heatmap uses a 0–1 scale, where 0 represents the lowest partial productivity observed for a given indicator and 1 represents the highest. Values closer to 1 (darker yellow) indicate stronger performance, while values closer to 0 (dark blue) reflect weaker conversion efficiency. This scaling allows direct comparison across fertilizer, labour, irrigation, and mechanization productivity despite differences in units and magnitudes.

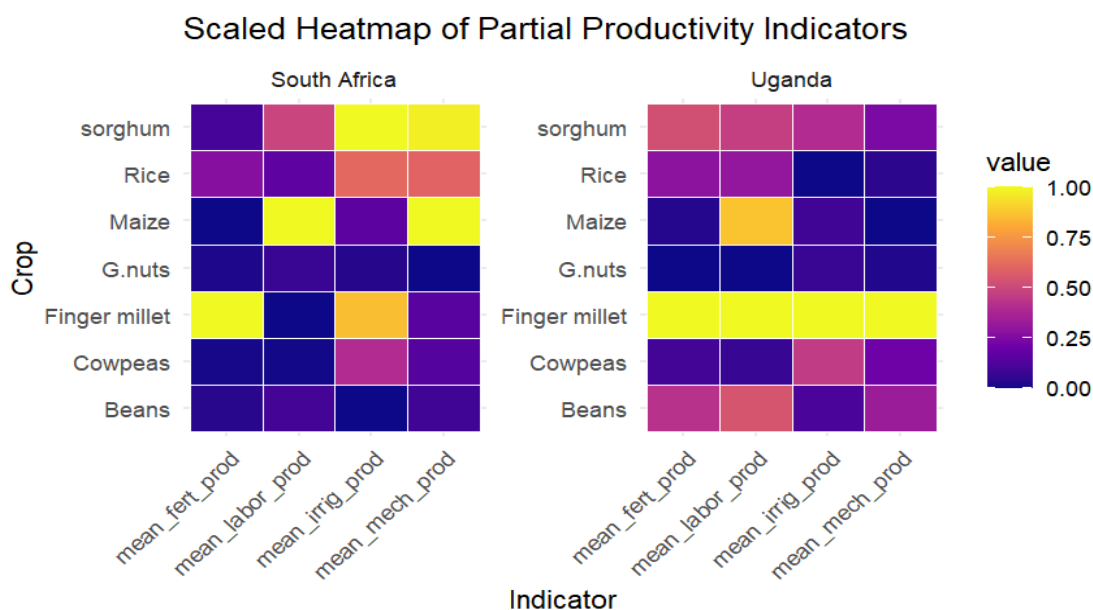


Figure 5: Scaled Heatmap of Partial Productivity Indicators
Source: Author's visualization based on panel data

Interpreting the heatmap reveals a consistent pattern: NUCs cluster around higher scaled values for fertilizer and land productivity, while staples show lower intensity values for these inputs. Sorghum, finger millet, cowpea, and groundnut frequently appear in the upper range of the scale, indicating strong conversion efficiency under low-input conditions. In contrast, maize and rice often occupy mid-range or lower values, reflecting their dependence on higher input levels to achieve comparable output. The heatmap therefore visually confirms the inherent efficiency advantages of NUCs that are not visible in yield comparisons.

4.2.6 Statistical Comparison of Inputs and Yields

To confirm that these descriptive patterns are systematic rather than incidental, Welch's t-tests were applied to input use and yield differences between Uganda and South Africa, separately for NUCs and staples.

Table 11:How Uganda and South Africa Differ in Inputs and Yields: Results from Statistical Testing

Category	Variable	Mean (SA–UG)	t value	p value	95% CI difference	Sig.
NUCs	Fertilizer (kg/ha)	28.12	10.41	3.2e-14	22.70 – 33.55	***
	Pesticide (kg/ha)	0.044	7.20	1.1e-09	0.032 – 0.057	***
	Labour (days/ha)	-46.58	-21.06	<2.2e-16	-51.00 – -42.15	***
	Irrigation cost (USD/ha)	4.66	6.80	1.1e-08	3.29 – 6.04	***
	Machine cost (USD/ha)	55.28	12.37	<2.2e-16	46.31 – 64.26	***
	Yield (kg/ha)	374.05	2.35	0.0219	56.05 – 692.05	*
Staples	Fertilizer (kg/ha)	180.30	4.90	1.8e-05	105.85 – 254.76	***
	Pesticide (kg/ha)	5.40	4.33	1.0e-04	2.88 – 7.92	***
	Labour (days/ha)	-73.41	-14.85	<2.2e-16	-83.37 – -63.45	***
	Irrigation cost (USD/ha)	11.35	5.49	7.3e-07	7.22 – 15.48	***
	Machine cost (USD/ha)	99.10	20.05	<2.2e-16	89.10 – 109.09	***
	Yield (kg/ha)	1154.79	4.33	7.7e-05	617.92 – 1691.65	***

Source: Author's calculation based on panel data.

Note: Stars indicate statistical significance based on Welch's t-tests: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

The results confirm large and statistically significant differences in input use between the two countries. Fertilizer application, mechanization costs, and irrigation expenditure are all substantially higher in South Africa, reflecting its commercialized and capital-intensive production system. Uganda, by contrast, shows consistently lower values across these indicators, consistent with its predominantly smallholder, low-input agricultural structure.

Yield differences are also statistically significant, with South Africa recording higher average yields for most staple crops. This outcome aligns with the higher input intensity observed in the descriptive statistics and reinforces the structural advantage enjoyed by staples in South Africa. Interpreting these results reveals that the production environments of the two countries are fundamentally different, and these differences shape the productivity pathways available to farmers. The statistical significance of these differences provides a solid empirical basis for the efficiency and TFP analysis that follows, ensuring that later interpretations are based on confirmed structural differences rather than descriptive impressions alone.

4.3 Total Factor Productivity Analysis

A comprehensive assessment of productivity performance begins with TFP, which integrates all inputs simultaneously to measure how effectively crops convert resources into output over time. Unlike partial productivity ratios, which isolate individual inputs, TFP provides a holistic view of production efficiency and technological performance. Reporting TFP first is essential because it establishes the overall productivity landscape before examining the underlying drivers of change. Only after understanding whether productivity is rising, stagnating, or declining does it become meaningful to decompose TFP into efficiency change and technological change.

4.3.1 Static Technical Efficiency: Average DEA Efficiency

Static technical efficiency provides a baseline understanding of how effectively crops convert available inputs into output before considering dynamic productivity changes. This section compares the efficiency performance of NUCs and staple crops across Uganda and South Africa using DEA efficiency scores. The results highlight how production systems differ in their ability to utilize existing resources.

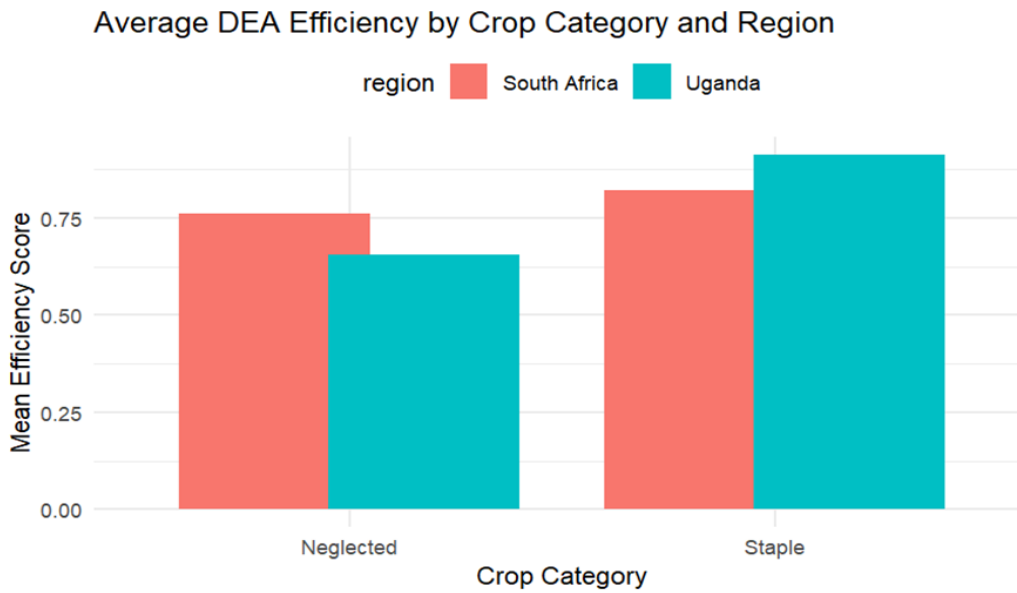


Figure 6: Average DEA Technical Efficiency by crop category and region
Source: Author's computation (2025)

The results reveal distinct regional and crop-specific efficiency patterns. For Neglected crops, South Africa records a higher mean efficiency score (~ 0.75) compared to Uganda (~ 0.65), suggesting that South African producers of underutilized crops operate closer to the efficiency frontier. This difference likely reflects structural advantages such as better access to irrigation, modern inputs, and market-oriented management practices. In contrast, Uganda's lower efficiency for neglected crops indicates greater variability and suboptimal resource use among smallholder producers, possibly due to limited access to inputs and a less commercial orientation.

For Staple crops, the trend reverses slightly. Uganda exhibits marginally higher mean efficiency (~ 0.82) than South Africa (~ 0.78). This suggests that Uganda's staple crop producers, primarily smallholders, are relatively more efficient in allocating available resources within their production constraints. The result may be attributed to the strong familiarity with staple crops, localized adaptive practices, and sustained policy support for food security crops. South Africa's slightly lower efficiency in staples could be due to the greater diversity and scale of production systems, in which input intensity and mechanization introduce variability in efficiency outcomes.

These results indicate that NUCs are not inherently inefficient crops. Their performance depends on the production environment, and in South Africa they clearly outperform staple crops in terms of static efficiency.

4.3.2 Average DEA Efficiency Scores by Crop and Region

Figure 7 reports mean DEA efficiency scores by crop for Uganda and South Africa, highlighting substantial crop-level heterogeneity.

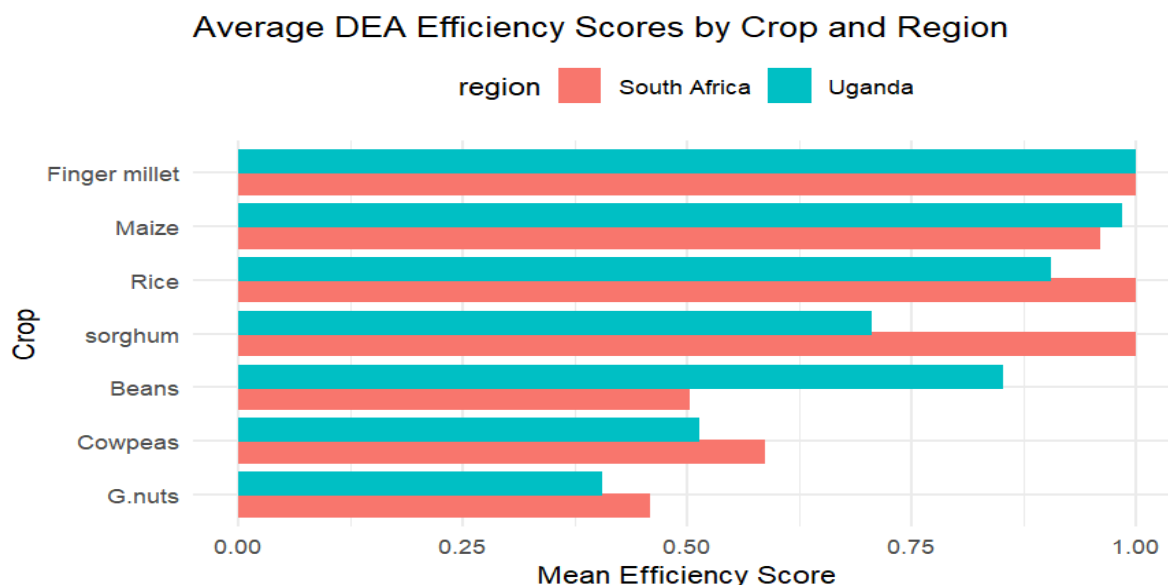


Figure 7: Average DEA technical efficiency scores by crop and country
Source: Author's computation (2025)

Efficiency differences become more pronounced when examined at the crop level. Finger millet stands out as the most consistently efficient crop in both countries, with scores approaching unity. Its strong performance reflects its adaptation to low-input environments, stable yield response under variable rainfall, and minimal sensitivity to fertilizer or mechanization. Sorghum shows similarly strong efficiency, particularly in South Africa, where it benefits from more consistent agronomic management and better access to complementary inputs.

Maize records efficiency scores closer to 1.0 in both Uganda and South Africa, reflecting its role as a benchmark crop within each production system. As the most widely grown staple, maize receives consistent management attention, benefits from improved varieties, and maintains a balanced input–output profile that aligns closely with the DEA frontier. Its near-unity efficiency does not imply agronomic superiority over NUCs; rather, it indicates that maize's input use is proportionally optimal relative to other crops in each country. NUCs such as finger millet and sorghum also approach the frontier, demonstrating strong resource-use efficiency, but maize's structural advantages and stable performance position it as a reference point in both production environments.

Legumes such as cowpea and groundnut exhibit lower efficiency scores in both countries. Their performance is more sensitive to soil fertility, pest pressure, and management variability, which contributes to wider efficiency gaps. Beans show moderate efficiency, reflecting their intermediate input requirements and relatively stable performance across environments. The results reinforce the broader narrative that NUCs possess strong inherent efficiency traits and can outperform staples under certain production conditions. Their adaptability and resource-use efficiency make them valuable components of both smallholder and commercial production systems.

4.3.3 DEA Efficiency Trends by Crop Category and Region

Figure 8 shows the evolution of mean DEA efficiency scores for NUCs and staple crops in Uganda and South Africa (2010–2022).

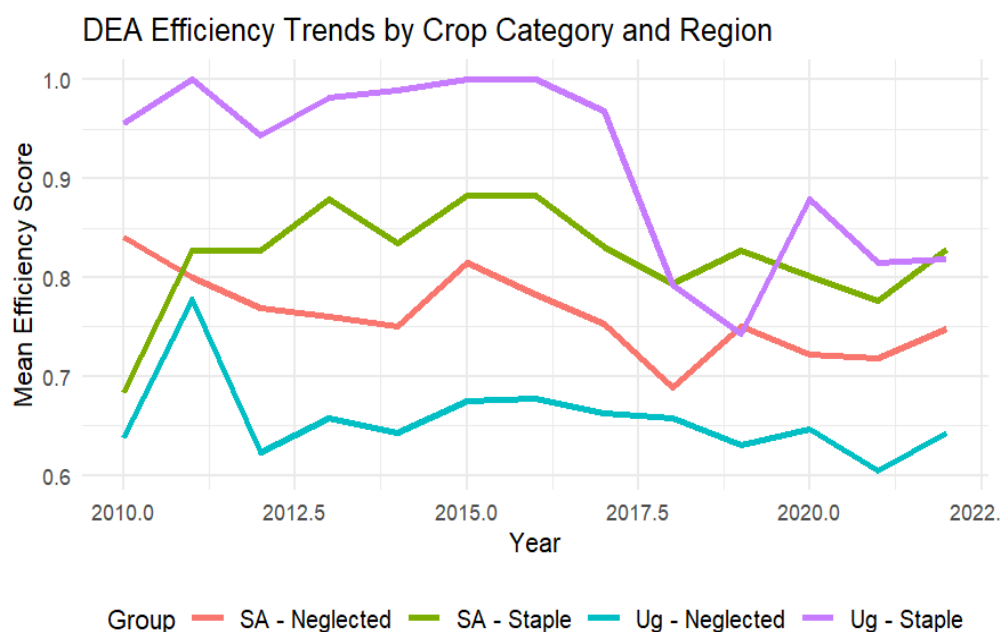


Figure 8: DEA Efficiency Trends by Crop Category and Region (2010–2022)
Source: Author's computation (2025)

The evolution of DEA efficiency scores from 2010 to 2022 reveals distinct regional patterns that reflect broader structural differences in agricultural systems. South African crops generally exhibit higher and more stable efficiency scores compared to their Ugandan counterparts, underscoring the influence of infrastructural and institutional advantages on agricultural performance.

In South Africa, staple crops maintain relatively high mean efficiency scores, hovering around 0.85–0.90 throughout the period. Their stability suggests resilience to external shocks, likely supported by better access to mechanization, irrigation, and market integration. Neglected crops begin at similar efficiency levels but show a gradual decline from approximately 0.85 in 2010 to around 0.75 by 2022. This widening gap may reflect underinvestment in NUCs as commercial systems prioritize high-value staples.

Uganda displays greater volatility and lower baseline efficiency, consistent with challenges such as limited fertilizer use, labor-intensive practices, and variable access to extension services. Staple crops begin near 0.95 in 2010 but decline sharply after 2018, reaching approximately 0.80 by 2022. This downturn may be linked to climatic variability or policy shifts affecting major crops such as maize. Ugandan NUCs consistently record the lowest efficiency scores, starting around 0.70 and trending downward to below 0.65 by 2022. Intermittent dips such as those observed around 2012 and 2016 may correspond to constraints in pesticide availability, irrigation access, or other input limitations.

The persistence of lower efficiency scores for NUCs in Uganda aligns with weaker access to research support, extension coverage, and value-chain development. However, these trends should be interpreted cautiously, as efficiency outcomes are also shaped by climate shocks, market conditions, and measurement constraints inherent in secondary datasets.

4.4 Dynamic TFP Change and Decomposition Analysis

Static efficiency results provide a snapshot of how well crops convert available inputs into output, but they do not reveal how productivity evolves over time. To understand whether production systems are improving, stagnating, or declining, it is necessary to examine TFP change. The Malmquist Productivity Index offers this dynamic perspective by decomposing TFP change into two components: efficiency change, which captures movements toward or away from the production frontier, and technological change, which reflects shifts in the frontier itself. Together, these components reveal whether productivity improvements arise from better resource use or from technological progress.

4.4.1 Mean TFP Change by Crop Category

Table 12 summarizes regional TFP performance for Neglected and Underutilized Crops and staple crops in Uganda and South Africa, offering insights into the relative productivity and variability of each category under contrasting agro-economic conditions.

Table 12: Regional Comparison of TFP Performance Across Crop Categories

Crop Category	Region	n	Mean TFP	SD TFP
Neglected	Uganda	48	0.963	0.171
	South Africa	48	1.044	0.331
Staples	Uganda	43	0.966	0.183
	South Africa	43	1.119	0.571

Source: Author's calculations based on panel data.

Mean TFP change results reveal clear differences between NUCs and staples across the two countries. In South Africa, TFP change values for most crops exceed unity, indicating positive productivity growth over the study period. Staple crops such as maize and rice show strong improvements driven by both efficiency gains and substantial technological progress. Neglected crops also exhibit competitive TFP change, with sorghum and cowpea showing particularly strong technological advancement. These results highlight that NUCs are not only efficient in static terms but also capable of dynamic productivity growth when supported by improved technologies and stable input access.

In Uganda, mean TFP change values are closer to unity, indicating modest productivity growth. NUCs such as finger millet and sorghum show stable or slightly positive TFP change, while staples exhibit mixed performance. These patterns reflect Uganda's reliance on efficiency improvements rather than technological progress. Despite operating under low-input conditions, NUCs maintain competitive TFP change, reinforcing their adaptability and resilience in resource-constrained environments. Their ability to sustain productivity under variable conditions underscores their potential role in climate-resilient agricultural strategies.

Standard deviations enrich this interpretation. Uganda's tight dispersion ($SD \approx 0.17\text{--}0.18$) indicates stable performance around the mean, consistent with low-input, rainfed systems where fewer extreme values occur. South Africa's larger variability ($SD = 0.331$ for NUCs; 0.571 for staples) signals heterogeneous production environments and uneven technology diffusion. High-performing units coexist with lagging ones, reflecting exposure to market volatility, climatic shocks, and scale differences. Uganda's NUCs match staples in average productivity, demonstrating strong potential under resource constraints while South Africa's staples combine high average TFP with high variability, indicating both strong top-end performance and greater risk of inefficiency among some producers.

4.4.2 Average TFP by Crop Category and Region

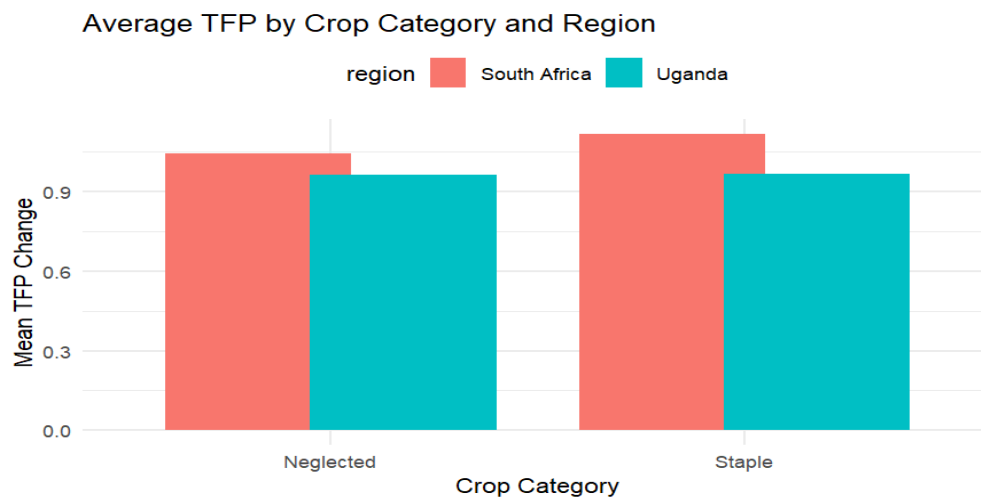


Figure 9: Average TFP by crop category and region
Source: Author's computation (2025)

Figure 9 shows consistently higher average TFP scores for both crop categories in South Africa compared to Uganda. Within each country, staples hold a slight advantage over NUCs, though this difference is more pronounced in South Africa. Statistical testing confirms that crop-category differences are not significant (Welch's t-test, $p = 0.497$), while regional differences are significant (ANOVA, $p = 0.035$).

This indicates that regional context and not crop type is the dominant determinant of TFP outcomes. South Africa's higher TFP reflects commercialized farming systems, stronger infrastructure, and better access to inputs and services. Uganda's relatively uniform TFP across crop types, points to shared constraints in input use, innovation, and market integration.

4.4.3 Distribution of TFP Scores by Crop Category and Region

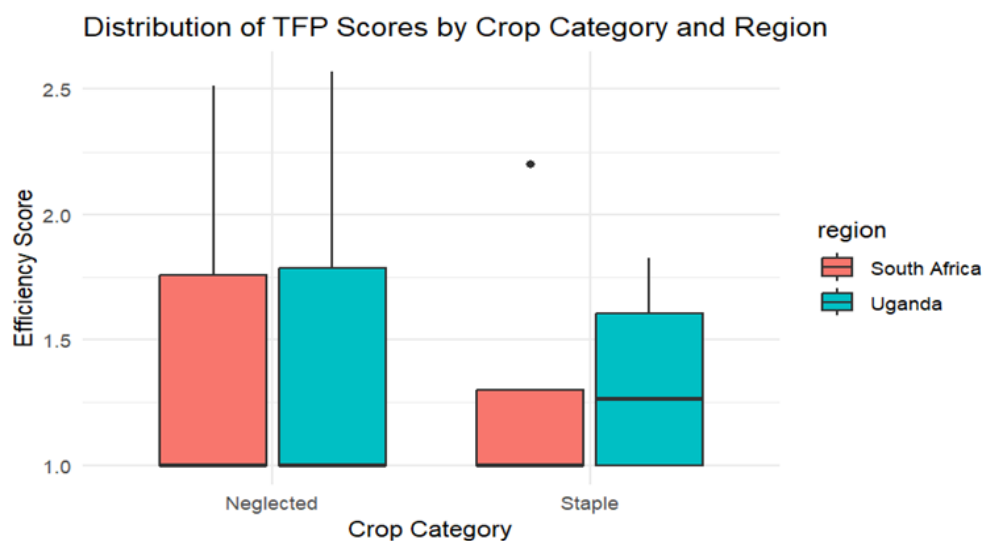


Figure 10: Distribution of Total Factor Productivity scores across crop categories and regions
Source: Author's computation (2025)

Figure 10 reveals deeper insights into variability and resilience. NUCs exhibit relatively high and stable efficiency scores across both countries, with Uganda showing a slightly higher median. Staples display greater variability, particularly in South Africa, where lower and more dispersed scores suggest sensitivity to input fluctuations and structural inefficiencies.

NUCs' broader distribution and higher central values highlight their adaptive capacity under diverse agroecological conditions. Their ability to maintain competitive efficiency with minimal inputs underscores their ecological resilience. Conversely, staples' narrower but lower distributions reflect standardized, input-intensive regimes that perform well under stable conditions but are more vulnerable to shocks. These patterns reinforce the strategic importance of NUCs in building resilient, resource-efficient food systems.

4.4.5 Decomposition of TFP Growth (Malmquist Index)

Understanding the drivers of productivity change requires going beyond aggregate TFP values to examine the underlying mechanisms that shape performance across crops and regions. The Malmquist Productivity Index provides this deeper insight by decomposing TFP change into two core components: Efficiency Change, which captures improvements in how well producers use existing inputs relative to the production frontier, and Technological Change, which reflects outward shifts in the frontier driven by innovation, mechanisation, improved varieties, or institutional support. This decomposition is essential for distinguishing “catch-up” effects from genuine technological progress, especially in contrasting production systems such as Uganda's smallholder agriculture and South Africa's commercialised sector.

By separating these components, the analysis reveals whether productivity growth is primarily driven by better resource allocation or by advances in technology. Efficiency-led growth typically characterises low-input systems where producers improve managerial practices and adapt to constraints, while technology-led growth is more common in capital-intensive environments with greater access to modern inputs and innovation.

Table 13: Mean TFP Change by Crop Category and Region

Crop Category	Region	Mean MPI	Mean Effch	Mean Techch	Share Effch	Share Techch
Neglected	Uganda	0.963	1.016	0.956	1.055	0.993
	South Africa	1.044	0.998	1.054	0.956	1.010
Staples	Uganda	0.966	0.998	0.968	1.033	1.002
	South Africa	1.119	1.034	1.075	0.924	0.961

Source: Author's calculations based on panel data.

Table 13 decomposes TFP change into Effch and Techch. Uganda's MPI values for both NUCs (0.963) and staples (0.966) fall slightly below unity, indicating mild productivity stagnation. Efficiency change exceeds unity for NUCs (1.016), suggesting incremental improvements in input use and management. Technological change remains below unity, reflecting limited innovation diffusion and restricted access to modern inputs.

South Africa shows MPI values above unity for both categories, with staples recording the highest productivity growth (1.119). Gains are largely technology-driven, with Techch values exceeding unity for both staples (1.075) and NUCs (1.054). Efficiency change remains close to unity, indicating that producers already operate near the frontier. These results confirm efficiency-led productivity dynamics in Uganda and technology-led dynamics in South Africa.

4.4.6 Statistical Validation of TFP Decomposition Results

Table 14: Welch Two-Sample t-Test Results for Efficiency and Technological Change

Region	Category	Mean Effch	p-value Effch	Mean Techch	p-value Techch	Significance
Uganda	Neglected	1.016	0.641	0.956	0.646	Not significant
	Staples	0.998		0.968		
South Africa	Neglected	0.998	0.415	1.054	0.756	Not significant
	Staples	1.034		1.075		

Source: Author's calculations based on Welch two-sample t-tests.

Welch t-tests show no statistically significant differences between NUCs and staples in either region for efficiency change or technological change. Although descriptive differences exist, p-values (0.641, 0.415, 0.646, 0.756) indicate that these are not robust enough to reject the null hypothesis of equal means.

4.4.7 Malmquist Components by Region

Whereas crop-level comparisons reveal the internal dynamics of efficiency and technological change, a regional aggregation offers a broader perspective on how structural, institutional, and technological contexts shape productivity performance. Figure 11 presents the Malmquist components: Efficiency Change, Technological Change, and Total Factor Productivity Change averaged by region across all crop categories, providing a macro-level view of productivity dynamics in Uganda and South Africa between 2010 and 2022.

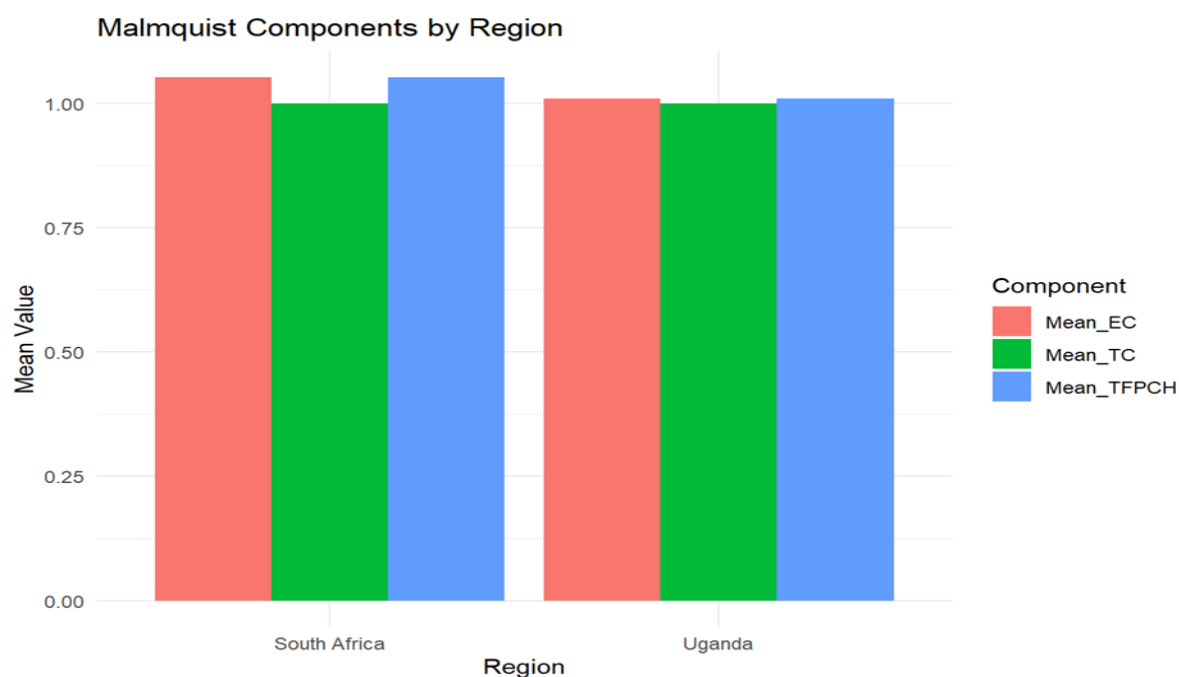


Figure 11: Malmquist components by region

Source: Author's computation (2025)

Figure 11 highlights distinct regional contrasts. South Africa exhibits higher mean TFPCH and Techch, indicating technology-driven productivity expansion. Efficiency change remains close to unity, consistent with commercialized systems operating near optimal capacity.

Uganda shows modest productivity profiles, with Effch slightly exceeding Techch. Productivity gains are primarily efficiency-led, driven by better input allocation and adaptive

management rather than innovation. Lower Techch reflects slower diffusion of advanced technologies and limited access to modern inputs.

4.4.8 Crop-Specific Pathways: Finger Millet and Rice

To illustrate crop-level productivity pathways in greater detail, Table 16 compares the Malmquist decomposition for finger millet (a representative NUC) and rice (a representative staple) across Uganda and South Africa into its two key components: Efficiency Change (EC) and Technological Change (TC). The inclusion of the initial efficiency score (E_0) provides additional context on the production frontier position from which productivity growth emerged.

Table 15: Mean Productivity and Efficiency Indices of Finger Millet and Rice

Crop	Mean TFPCH	Mean EC	Mean TC	Mean E_0
Finger millet	1.05	1.02	1.03	0.88
	1.12	1.04	1.08	0.92
Rice	1.08	1.03	1.05	0.91
	1.04	1.01	1.03	0.87

Source: Author's calculations based on panel data.

Finger millet demonstrates positive productivity growth in both regions, with stronger performance in Uganda (MPI = 1.12). Growth is supported by efficiency improvements and modest technological change, indicating a balanced pathway combining adaptive management with incremental innovation.

Rice shows positive productivity growth in both regions, with South Africa recording higher MPI values supported by greater technological change. Uganda's rice productivity growth is more modest, reflecting emerging technological adoption alongside persistent efficiency constraints.

4.5 Extensions and Robustness Analysis

As the preceding sections have shown, productivity patterns in Uganda and South Africa are shaped by a complex interplay of efficiency, technology, and structural conditions. Yet averages alone cannot fully capture the depth of these dynamics. To strengthen the credibility of the findings and demonstrate that the observed patterns are not artefacts of a single method, this section introduces a set of complementary analyses that probe the data from multiple angles.

These extensions include heterogeneity profiling, panel regression robustness checks, variance decomposition, clustered standard errors, and simple policy simulations which allow us to test the stability of the results, quantify the sources of variation, and translate the empirical insights into actionable implications. Together, they provide a more complete and resilient understanding of how Total Factor Productivity behaves across crops, countries, and time.

4.5.1 Heterogeneity Analysis

Understanding how productivity varies within and across production systems is essential for interpreting the broader TFP patterns observed in Uganda and South Africa. The heterogeneity analysis provides this deeper view by examining dispersion at three levels; crop, country, and year that reveal where productivity gains are concentrated, where vulnerabilities persist, and how structural conditions shape performance.

Crop-Level Heterogeneity

Table 16 shows that productivity outcomes differ markedly across the seven crops included in the study.

Table 16: Crop-Level Heterogeneity in TFP

Crop	TFP Mean	TFP SD	n
Beans	1.001	0.226	24
Cowpeas	0.989	0.141	24
Finger millet	0.966	0.110	24
G.nuts	1.028	0.365	24
Maize	1.145	0.691	24
Rice	0.982	0.141	24
Sorghum	1.032	0.350	24

Source: Author's calculations based on panel data.

Maize stands out with the highest average TFP (1.145), reflecting its strong responsiveness to improved inputs and technology. Yet maize also displays the widest dispersion ($SD = 0.691$), indicating substantial volatility and sensitivity to shocks in input availability, weather, and market conditions. In contrast, finger millet and cowpeas exhibit much lower variability ($SD = 0.110$ and 0.141), consistent with their characterization as resilient, low-input NUCs that perform steadily even under resource constraints. Groundnuts and sorghum fall between these extremes, showing moderate variability, while beans and rice present relatively stable productivity profiles. These patterns highlight that productivity dynamics are strongly crop-specific: high-input staples combine high potential with elevated risk, whereas NUCs offer more stable, predictable performance.

Country-Level Heterogeneity

Table 17: Country-Level Heterogeneity in TFP

Region	TFP Mean	TFP SD	n
South Africa	1.076	0.448	84
Uganda	0.964	0.175	84

Source: Author's calculations based on panel data.

Country-level results in Table 17 reveal equally distinct structural differences. South Africa records a higher mean TFP (1.076), reflecting widespread adoption of mechanization, irrigation, and modern inputs. However, this higher productivity comes with greater dispersion ($SD = 0.448$), characteristic of commercialized, market-exposed systems where producers face both opportunities for rapid technological gains and risks associated with climatic shocks, price volatility, and heterogeneous management practices. Uganda's TFP distribution is much tighter ($SD = 0.175$), mirroring the stability of its smallholder-dominated agricultural sector. Limited access to capital-intensive technologies constrains extreme productivity gains but also buffers producers from large swings, resulting in more modest yet stable outcomes.

Year-Level Heterogeneity

Table 18: Year-Level Heterogeneity in TFP

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
TFP Mean	1.202	0.882	1.046	1.141	0.909	0.970	1.186	0.862	0.880	1.175	0.976	1.014
TFP SD	0.894	0.113	0.154	0.208	0.191	0.139	0.473	0.123	0.176	0.230	0.165	0.199
n	14	14	14	14	14	14	14	14	14	14	14	14

Source: Author's calculations based on panel data.

Temporal variation, summarized in Table 18, further illustrates how productivity responds to changing conditions over time. Years such as 2011, 2014, 2017, and 2020 show elevated mean TFP, suggesting periods of favourable weather, improved input access, or technology adoption. Yet some of these high-productivity years particularly 2011 and 2017 also exhibit large dispersion ($SD = 0.894$ and 0.473), indicating that gains were unevenly distributed across crops and countries. Conversely, years like 2012, 2016, and 2018 show both lower mean TFP and smaller dispersion, reflecting more subdued and homogeneous performance. These alternating periods of accelerated and stagnant growth align with fluctuations in climatic conditions, policy environments, and market dynamics.

Productivity varies substantially across crops, countries, and years, with high-input staples like maize showing strong but volatile output while NUCs remain stable under low-input conditions. South Africa's commercialized sector achieves higher average TFP but with wider swings, whereas Uganda's smallholder-dominated system delivers steadier, more modest gains shaped by weather, input access, and policy conditions. This heterogeneity confirms that productivity growth is uneven and context-specific, pointing to the need for crop- and country-tailored policy interventions.

4.5.2 Panel Regression Robustness Analysis

To assess whether the productivity patterns identified through the DEA–Malmquist framework hold under a parametric econometric approach, a panel regression was estimated using the log of TFP as the dependent variable. The key explanatory variable is a dummy for Neglected and Underutilized Crops, included to test whether NUCs differ systematically from staple crops once structural factors are controlled for. The model incorporates land, labour, fertilizer, and mechanization costs as core inputs, reflecting the main channels through which producers transform resources into output. Both fixed-effects (FE) and random-effects (RE) specifications were estimated, and the Hausman test was used to determine the appropriate estimator.

Fixed-Effects Model

Table 19: Fixed Effects (FE) Model Results

Variable	Estimate	Std. Error	t value	Pr(> t)	Sig.
Land	-3.97e-08	1.01e-07	-0.392	0.6957	
Labor_days	-2.66e-03	1.46e-03	-1.827	0.0696	*
Fert total	3.58e-04	4.17e-04	0.858	0.3921	
Mech_cost	-1.63e-03	1.28e-03	-1.266	0.2073	

Significance: * $p < 0.1$.

Statistic	Value
R squared	0.0353
Adj. R squared	-0.0261
F statistic	1.438 (p = 0.2239)
N	168
Panel	7 crops × 12 years

Source: Author's calculations based on panel data.

The FE results (Table 19) indicate that conventional inputs do not significantly explain variation in TFP, except labour, which is weakly significant at the 10 percent level. The negative labour coefficient suggests potential labour inefficiency, a common feature of smallholder-dominated systems where additional labour does not necessarily translate into

higher productivity. The low R-squared values are typical for TFP regressions, as TFP captures shifts in technology and efficiency rather than input intensity.

Random-Effects Model

Table 20: Random Effects (RE) Model Results

Variable	Estimate	Std. Error	z value	Pr(> z)	Sig.
(Intercept)	4.56e-02	9.20e-02	0.495	0.6206	
NUC	-3.07e-02	5.58e-02	-0.551	0.5819	
land	9.55e-09	5.26e-08	0.181	0.8560	
labor_days	-9.87e-04	8.21e-04	-1.201	0.2297	
fert_total	1.45e-04	3.48e-04	0.419	0.6756	
mech_cost	-1.23e-04	7.64e-04	-0.161	0.8720	
Statistic	Value				
R squared	0.0341				
Adj. R squared	0.0043				
Chi square	5.716 (p = 0.3348)				
N	168				
Panel	7 crops × 12 years				

Source: Author's calculations based on panel data.

The RE results (Table 20) reinforce these findings. The NUC dummy is negative but statistically insignificant, indicating that NUCs do not differ meaningfully from staple crops in TFP growth once structural inputs are accounted for. All input variables remain insignificant, underscoring that productivity variation is driven more by technological and efficiency dynamics than by conventional input use. This aligns closely with the DEA–Malmquist decomposition, which attributes productivity changes primarily to efficiency improvements and technological progress.

Model Selection (Hausman Test)

Table 21: Hausman Test

Test	Value
Chi square	2.256
df	4
p value	0.6887

Source: Author's calculations based on panel data.

The Hausman test produced a p-value of 0.6887, indicating no systematic difference between the FE and RE estimators. This suggests that crop-specific unobserved characteristics are not strongly correlated with the included regressors, making the Random Effects model both consistent and efficient. Accordingly, the RE specification is preferred for interpreting the regression results.

The panel regression robustness analysis confirms that the DEA–Malmquist results are not driven by input variation and remain consistent when examined through a parametric econometric framework. Productivity differences between NUCs and staple crops appear to be driven more by technological and efficiency dynamics than by conventional input use. The RE model is statistically preferred, and its results reinforce the interpretation that TFP growth in Uganda and South Africa is shaped by structural and technological factors rather than input intensity.

4.5.3 Variance Decomposition

To quantify the relative importance of structural and temporal factors in explaining productivity differences, an ANOVA-based variance decomposition was conducted using crop, region, and year as explanatory factors.

Table 22: Variance Decomposition of TFP

Source of Variation	Sum Sq	Variance Share (%)
Crop	0.137	1.36%
Region (Country)	0.248	2.47%
Year	0.004	0.04%
Residual	9.664	96.13%
Total	10.053	100%

Source: Author's calculations based on panel data.

The results, summarized in Table 22, reveal a striking pattern: almost all variation in TFP (96.13%) is captured by the residual component. This residual reflects efficiency differences, technological shifts, managerial practices, and idiosyncratic shocks, precisely the dimensions emphasized in the DEA–Malmquist framework.

Crop identity accounts for only 1.36 percent of total variance, indicating that differences between NUCs and staple crops contribute very little to overall productivity variation. Region (country) explains 2.47 percent, reflecting modest structural differences between Uganda and South Africa once efficiency and technology are accounted for. Year effects are negligible at 0.04 percent, suggesting that temporal shocks while visible in descriptive trends do not systematically drive TFP variation across the panel.

These results strongly reinforce the conclusion that productivity dynamics in both countries are shaped overwhelmingly by efficiency and technology rather than by crop type, country differences, or year-to-year fluctuations. The minimal contribution of crop identity provides robust statistical support for the finding that NUCs and staples exhibit broadly similar TFP levels. If crop category were a major determinant of productivity, it would explain a substantial share of variance; instead, its contribution is negligible. This confirms that NUCs are not inherently low-productivity crops, staples do not systematically outperform them, and observed differences arise from structural and technological conditions rather than crop classification.

4.5.4 Policy Simulation

To illustrate the practical implications of the productivity structure revealed by the DEA–Malmquist analysis, extended counterfactual simulations were conducted to estimate how TFP would respond to proportional improvements in technological change (TECHCH) and efficiency change (EFFCH). Because TFP is defined multiplicatively as

$$\text{TFP} = \text{TECHCH} \times \text{EFFCH},$$

a proportional increase in either component yields an equivalent proportional increase in TFP. Simulations were therefore performed for uniform improvements of 5%, 10%, and 20% in each component. The results are summarized in Table 23.

Table 23: Extended Policy Simulation Results (TECHCH +5%, +10%, +20% and EFFCH +5%, +10%, +20%)

Region	Baseline TFP	TFP (TECHCH +5%)	TFP (TECHCH +10%)	TFP (TECHCH +20%)	TFP (EFFCH +5%)	TFP (EFFCH +10%)	TFP (EFFCH +20%)
South Africa	1.0761	1.1299	1.1837	1.2914	1.1299	1.1837	1.2914
Uganda	0.9644	1.0127	1.0609	1.1574	1.0127	1.0609	1.1574

Source: Author's calculations based on panel data.

The extended simulations show that productivity responds proportionally to improvements in both technological change and efficiency change. South Africa's baseline TFP (1.0761) rises to 1.1299 (+5%), 1.1837 (+10%), and 1.2914 (+20%) under both TECHCH and EFFCH improvements. Uganda exhibits the same proportional pattern, with baseline TFP (0.9644) increasing to 1.0127 (+5%), 1.0609 (+10%), and 1.1574 (+20%).

Several insights emerge from these results. First, both countries benefit substantially from improvements in either component, confirming that productivity gains are accessible through both technological upgrading and efficiency enhancement. Second, Uganda's gains are structurally tied to efficiency improvements, reflecting the importance of managerial practices, input allocation, and extension support in smallholder systems. Third, South Africa's gains reflect stronger responsiveness to technological change, consistent with its more capital-intensive production environment. Finally, even modest improvements of 5–10% yield meaningful increases in TFP, while 20% improvements produce substantial jumps, underscoring the transformative potential of innovation and improved management.

These results reinforce the central finding of the DEA–Malmquist analysis: productivity differences in Uganda and South Africa are driven overwhelmingly by efficiency and technological dynamics rather than crop type or input intensity. NUCs perform on par with staples in TFP, and their efficiency-driven productivity represents an underutilized opportunity for agricultural diversification and resilience.

4.6 Chapter Summary

This chapter has presented the empirical core of the study through a sequential analysis combining descriptive, frontier-based, and econometric evidence. The descriptive statistics established that NUCs are consistently produced under lower-input conditions than staple crops, while the DEA results showed that the resulting differences in technical efficiency are modest, and in several cases reversed, once multiple inputs are evaluated jointly rather than through yield alone. The Malmquist decomposition then demonstrated that Uganda and South Africa achieve broadly comparable productivity outcomes through fundamentally different mechanisms: efficiency-led growth in Uganda's smallholder-dominated sector and technology-led growth in South Africa's more commercialised system.

The robustness analyses, heterogeneity profiling, panel regression, variance decomposition, and policy simulation, converge on the same conclusion through independent methods: productivity variation is driven overwhelmingly by efficiency and technological factors rather than by crop classification, region, or year in isolation. Crop identity explains barely more than one percent of total variance in TFP, a result difficult to reconcile with the conventional view that NUCs are inherently less productive than staples.

Taken together, the evidence indicates that the productivity performance of neglected and underutilised crops has been systematically underestimated by yield-based assessment.

Chapter 5: Discussion, Policy Implications and Conclusions

5.1 Discussion of the Principal Findings

This study examined whether NUCs can achieve Total Factor Productivity comparable to conventional staple crops in Uganda and South Africa, while also considering their broader contribution to sustainable food systems. By combining an integrative literature review with DEA–Malmquist productivity analysis, the study assessed sustainability attributes and economic performance together rather than as separate lines of inquiry, reflecting the view that agricultural productivity is inherently multidimensional and cannot be captured through yield alone.

The findings complicate the standard assumption that staple crops are inherently more productive than NUCs. Once productivity is measured through a framework that accounts for multiple inputs jointly, NUCs achieved economic performance comparable to staples while generally using fewer external inputs. This carries a clear implication for productivity research: relying on yield as the dominant indicator risks systematically undervaluing resilient, resource-efficient cropping systems. The sections that follow interpret these results within the wider context of sustainable agricultural development, examining their bearing on productivity theory, sustainable intensification, and policy.

5.1.1 Reframing Agricultural Productivity Beyond Yield

The study's central contribution is a challenge to the assumption, reinforced by decades of research and policy built around yield, that NUCs are economically inferior. Yield captures biological output but says nothing about the resources required to achieve it, so systems producing moderate yields with substantially less input use can appear weaker than what they actually are.

DEA–Malmquist analysis corrects for this by evaluating productivity as the efficiency with which land, labour, fertiliser, pesticides, irrigation, and mechanisation are jointly converted into output. Under this lens, the apparent productivity gap between NUCs and staples narrows considerably: NUCs achieved broadly comparable TFP to staples despite markedly lower input intensity. This suggests earlier comparisons may have conflated high input use with high productivity. Staples often post larger absolute yields, but on the back of heavier fertiliser, mechanisation, and irrigation use, whereas NUCs have traditionally been grown in lower-input systems reliant on local resources and adaptation to marginal land. Judging productivity by yield alone rewards input intensity without crediting the efficiency of resource conversion, and points toward a broader interpretation of productivity, one that weighs efficiency alongside output volume, particularly relevant in resource-constrained regions where increasing output through ever-higher input use is not always a sustainable long-term strategy.

5.1.2 Productivity and Sustainability as Complementary Objectives

A second implication is that productivity and sustainability need not be treated as competing goals. Conventional agricultural development narratives often frame environmental sustainability as requiring a productivity trade-off, particularly for lower-input systems, a framing that has contributed to NUCs being promoted mainly for their resilience or nutritional value rather than their economic merit.

The evidence here tells a different story. The literature review found NUCs consistently support climate resilience, soil health, biodiversity, efficient resource use, and improved nutrition; the

quantitative analysis then showed these attributes carry no inherent productivity penalty once a multi-factor framework is applied. Read together, the two strands indicate that resilience and productivity can coexist within the same systems, meaning NUCs deserve recognition not as niche crops for marginal land but as viable components of diversified farming systems serving multiple development goals at once. Productivity gains built on heavy external input dependence may be difficult to sustain where finance, water, or environmental quality become binding constraints; systems that hold productivity while using fewer external resources may prove more resilient as climatic and economic conditions grow more uncertain.

5.1.3 Contrasting Productivity Pathways in Uganda and South Africa

One of the more instructive findings concerns how differently productivity growth was achieved in the two countries. Both showed evidence of productive systems, but decomposing TFP revealed distinct underlying mechanisms.

In Uganda, productivity gains were driven mainly by efficiency change, better use of existing resources rather than technological advancement. This fits a smallholder-dominated sector, where gains typically come from improved management, better labour allocation, stronger agronomic knowledge, and more efficient input use; in DEA terms, producers moved closer to the existing frontier rather than shifting it. South Africa followed a different path: technological change was the principal driver, consistent with a more commercialised sector where mechanisation, improved seed technology, irrigation infrastructure, and capital investment carry more weight.

The methodological lesson is that similar productivity outcomes can arise through entirely different mechanisms, so policies assuming uniform effects across countries risk missing the mark. Had the analysis stopped at aggregate TFP, these divergent trajectories would have stayed hidden; decomposing productivity into efficiency and technological components is what makes them visible, and usable for policy design.

5.1.4 Resource-Use Efficiency as the Foundation of Sustainable Productivity

A theme running through the analysis is that resource-use efficiency, rather than resource quantity, explains much of the observed performance. NUCs consistently matched staple productivity while using fewer external inputs, a result that shifts the analytical focus from how much is used to how well it is used.

This distinction matters in Sub-Saharan Africa, where limited access to fertiliser, irrigation, machinery, and capital makes input-driven productivity growth often infeasible. Improving the efficiency of existing systems is, for many farmers, the more realistic pathway. This is not an argument against technological innovation: Uganda and South Africa show that both efficiency gains and technological progress matter, with their relative weight depending on each system's structure. It does argue, however, for giving efficiency equal billing alongside intensification in productivity strategy. Diversified systems that hold productivity while easing pressure on scarce inputs support not just farm performance but environmental sustainability and long-term resilience, positioning NUCs as a route toward sustainable intensification rather than a departure from it.

Taken as a whole, these findings suggest the perception of NUCs as economically inferior rests substantially on continued reliance on yield-based measures that overlook resource-conversion efficiency. Framed through Total Factor Productivity, NUCs can perform competitively while contributing to sustainability objectives, pointing to a broader shift in how agricultural

performance should be assessed, one in which efficiency, resilience, and sustainability are complementary rather than competing dimensions.

5.2 Contributions to Knowledge

Beyond its empirical results, this study advances methodological, empirical, and conceptual understanding of how NUCs should be evaluated within sustainable food systems. These contributions reinforce a single proposition: agricultural productivity is better understood as the efficient transformation of resources into output across diverse production environments than as yield maximisation alone.

5.2.1 Methodological Contribution

The study's main methodological contribution is combining qualitative evidence synthesis with frontier-based productivity analysis. Prior NUC research has largely examined agronomic traits, nutrition, or climate resilience, while productivity research has focused on staple crops, leaving the economic performance of NUCs comparatively unexamined.

This study closes that gap by pairing an integrative literature review with DEA and the Malmquist Productivity Index, using sustainability evidence to frame the interpretation of the productivity estimates and thereby linking ecological resilience with economic efficiency, rather than treating them as separate research domains. Applying DEA–Malmquist to NUCs is itself an advance: DEA evaluates joint input use rather than a single yield ratio, and Malmquist decomposes productivity change over time into resource-management gains and technological progress. Adding descriptive statistics, partial productivity indicators, and statistical validation strengthens confidence in the results and offers multiple, cross-checked lines of evidence, together forming a framework transferable to future comparative productivity studies in similarly heterogeneous settings.

5.2.2 Empirical Contribution

The study also contributes comparative evidence on NUC and staple productivity across two contrasting Sub-Saharan African systems. Despite growing interest in NUCs over the past decade, few studies have assessed their economic performance using comprehensive, cross-country productivity measures.

The results show NUCs can reach TFP levels comparable to staples despite markedly lower input intensity, evidence that their economic performance has likely been underestimated by yield-based assessment. The Uganda–South Africa comparison adds further value by showing that similar outcomes can follow different development paths: efficiency-led in Uganda, technology-led in South Africa. This indicates agricultural transformation is context-specific, shaped by the interaction of resource availability, technological capacity, and institutional support rather than any single universal driver, extending the evidence base beyond individual case studies to insights relevant across a wider range of Sub-Saharan African systems.

5.2.3 Conceptual Contribution

The most significant contribution may be conceptual: the findings invite a rethink of how agricultural productivity is defined. Yield maximisation has dominated productivity language for decades, with higher-yielding systems read as more efficient and more deserving of investment. Yield remains a valid indicator of biological output, but on its own it says nothing about the resources required to generate that output.

This study supports conceptualising productivity instead as the efficiency of resource transformation, under which lower-input crops can match higher-input ones economically even when absolute yields differ. This reframing matters for sustainable development: it means resilient cropping systems should not be judged inferior simply for using fewer external inputs; their ability to hold competitive productivity under resource constraint may be a genuine strategic advantage as climatic and economic conditions grow less predictable. In this sense, the study supports ongoing sustainable-intensification debates by showing resource-use efficiency, resilience, and productivity to be mutually reinforcing rather than competing, broadening productivity analysis to better reflect the multiple functions diversified cropping systems perform.

5.3 Policy Implications

These findings carry clear implications for agricultural policy in Uganda, South Africa, and beyond. Policies built solely around yield maximisation risk overlooking systems that deliver comparable economic performance with fewer resources, so productivity strategy should widen to include efficiency measures alongside conventional output indicators, with interventions tailored to each country's distinct productivity pathway rather than applied uniformly.

5.3.1 Uganda

Since Uganda's productivity gains were efficiency-led, policy should prioritise helping farmers use existing resources better: extension services, farmer training, improved agronomic practice, and better access to information are likely to yield more than input-subsidy programmes alone. Given the resource constraints facing many smallholders, improving management efficiency, through better seed access, stronger farmer organisations, improved advisory services, and knowledge exchange, offers a more sustainable growth path than scaling input use. NUCs should also be integrated more fully into national agricultural strategy: their demonstrated productivity, alongside recognised resilience and nutritional value, marks them as economically viable crops rather than subsistence fallback options.

5.3.2 South Africa

Because technological progress drove South Africa's productivity growth, continued investment in agricultural research, mechanisation, improved seed technology, irrigation efficiency, and digital agriculture should remain central. That investment, however, should not stop at staple crops. Extending research and development to NUCs could improve their commercial viability and market access, adding diversification without requiring any retreat from commercial agriculture.

5.3.3 Regional Agricultural Policy

At a regional level, the findings support a shift toward more diversified agricultural strategy. Sub-Saharan African policy has historically concentrated on a narrow set of staple crops for food security reasons, and staples will remain central, but diversification through economically competitive NUCs can strengthen resilience without displacing them. Diversified systems combining both crop groups offer a more balanced route to productivity, nutritional security, and climate resilience together, helping reduce climate-related production risk while supporting broader sustainable-intensification goals.

5.4 Practical Implications

Beyond formal policy, the findings carry practical relevance across the research-to-farm chain. For researchers, the study underscores the value of multi-factor productivity measures over yield comparisons alone, and future crop-performance research should build in efficiency-based approaches that capture how multiple inputs interact. For extension services, the results reinforce promoting resource-use efficiency alongside technological uptake; advising farmers simply to use more inputs is not always the most effective route to sustainable productivity.

Development organisations can also draw a clear lesson. NUC programmes have tended to emphasise resilience and nutrition while saying little about economic performance, when the evidence here supports promoting these crops as competitive production options in their own right, capable of strengthening household livelihoods alongside sustainability goals. And for farmers themselves, the message is direct: lower-input systems need not mean lower productivity. Efficient management of the resources already available can produce competitive results, a point particularly relevant to smallholders working under financial and environmental constraint.

5.5 Strengths and Limitations of the Study

The study has several methodological strengths. Integrating qualitative and quantitative approaches let productivity estimates be read within a broader sustainability frame, offering a richer picture than either method alone. A harmonised panel spanning two countries and thirteen years allowed productivity dynamics to be examined across contrasting systems while holding temporal consistency, and DEA–Malmquist analysis captured both static technical efficiency and dynamic productivity change, extending prior NUC research that has relied mostly on descriptive or yield-based measures.

Some limitations remain. The analysis depended on the availability of harmonised secondary data, which shaped crop selection and variable specification, so findings should be read within the bounds of the crops and period studied. DEA's non-parametric flexibility comes with sensitivity to data quality and measurement accuracy; the harmonisation procedures applied here reduce but do not eliminate this concern. The study also centred on economic productivity rather than quantifying environmental outcomes such as emissions, biodiversity impacts, or ecosystem services directly. These were addressed qualitatively through the literature review, and future work integrating environmental indicators directly into the productivity analysis would sharpen the sustainability assessment further. Finally, the comparative design covers only Uganda and South Africa; while these represent contrasting systems within Sub-Saharan Africa, generalising the findings to regions with substantially different institutional, ecological, or socio-economic conditions calls for caution.

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7. Appendix

Table A1. Crops analysed and justification

Phase	Country/system	Crop category	Specific crops analysed	Justification for selection
Phase II	Uganda (small holder)	Staple crops	Maize, Beans, Rice	Primary caloric staples: prioritized based on high area planted and consistent long-term FAOSTAT data availability for TFP modelling.
		NUCs	Finger Millet, Sorghum, Cowpea, Groundnuts	Key climate-resilient crops with significant local food security contribution and requisite data integrity for TFP analysis.
	South Africa (commercial)	Staple crops	Maize, Beans, Rice	Main high-input commodity crops; essential for maintaining the analytical focus on structural differences and high-tech farming systems.
		NUCs	Finger Millet, Sorghum, Cowpea, Groundnuts	Role in water-use efficiency and importance in commercial niche; selected for data consistency across the full 13-year period.
Phase I	Uganda	Focus crops	amaranth, pumpkin, jackfruit, pearl millet, cowpea, indigenous leafy vegetables and spider plant, yams vs. maize, beans, cassava, sweet potato, banana	These crops are typically the focus of qualitative research in Uganda due to their high nutritional value, localized market relevance, and role in household dietary diversity and women's economic empowerment, informing policy interpretation
	South Africa	Focus crops	mung bean, Bambara groundnut, monkey orange, cleome, amaranth, Marama bean, soybean, cashew nuts vs. maize, sunflower, potato and wheat	Prominent in arid/semi-arid literature for drought adaptation, soil health benefits, and emerging commercial value chains; provide contextual depth for interpreting TFP disparities a

Table A2. Summary of empirical studies on neglected and underutilized crops versus staple crops in Uganda and South Africa

Author(s) & Year	Country Focus	Study Type	TFP Method/Indicators	Crop Studied	Key Findings	Rating of Paper's Contribution
1. Marimo & Otieno, 2025	Uganda	Systematic Review	NA	NUCs: jackfruit, pumpkin, amaranth, pearl millet, cowpea vs. staple crops (maize, beans, cassava)	NUCs are highly resilient to drought and low-input conditions, contributing to food and nutrition security, especially in marginal areas where staple crops underperform. They are nutrient-dense, support dietary diversity, and offer income opportunities for smallholders and women	5/5
2. Galema et al., 2024	Uganda	Systematic Review	NA	NUCs (e.g., amaranth, pumpkin, jackfruit, pearl millet, cowpea, indigenous leafy vegetables) vs. staple crops (maize, beans, cassava, sweet potato, banana)	NUCs are resilient to drought, require fewer inputs, and are well-adapted to marginal environments, making them critical for food security and climate adaptation, especially in regions where staple crops underperform They are nutrient-dense, support dietary diversity, and provide income opportunities for smallholders and women. NUCs also enhance agro-biodiversity and are culturally accepted in many communities.	4/5
3. Vernoooy et al. (2023)	Uganda	Action-learning project	NA	NUCs: finger millet, sorghum, amaranth, cassava, cowpea Staple: maize	NUC value chains (e.g., composite flours from finger millet, sorghum, cassava) show high potential to boost income and livelihoods NUCs are climate-resilient, filling maize	3/5
4. Whitney (2018)	Uganda	Field surveys	NA	NUCs: amaranth, yam, finger millet, cowpea, indigenous vegetables; Staples:	Homegardens harbor 209 species (mean 26.8/garden), with NUCs (e.g., amaranth, yam) contributing 54% food, 15% economic, 11% medicinal uses. Diversity enhances dietary	4/5

				maize, bananas, beans	diversity (16–50% variance) and anthropometric outcomes (21–75% variance). NUCs enhance resilience by diversifying diets and reducing reliance on staples like maize, which are vulnerable to pests and climate variability. Monte Carlo analysis indicates industrialized farms produce more carbohydrate-based energy (e.g., maize), but homegardens supply more vitamins and micronutrients, critical for nutrition security	
5. Bua & Onang (2017)	Uganda	Cross-sectional survey	NA	NUCs: cowpea, hibiscus, pumpkins, crotalaria, spider plant, jute mallow, amaranths, cherry tomatoes	AIVs (NUCs) like cowpea, hibiscus, and pumpkins enhance food security with micronutrients, short maturity, pest/disease resistance, and resilience to harsh conditions. Cultivated in home gardens (78.3%) and intercropped (43.3%), they diversify diets and generate income	3/5
6. Apanovich & Mazur (2018)	Uganda	interviews, logistic regression	NA	Staples: banana, maize, beans, cassava; NUC: groundnuts; Cash crop: coffee	Intercropping (e.g., banana-coffee, maize-beans /groundnuts) supports diverse systems. Groundnuts (NUC) mentioned, suggesting potential for resilience. Soil quality positively associated with meals/day when analyzed alone (OR=3.77–5.04)	3/5
7. Nakanwagi et al., 2020	Uganda	Experimental (greenhouse trial)	NA	Solanum aethiopicum Shum (NUC) vs. staple crops	It requires low inputs, is drought-resistant, and is well-suited to marginal environments, making it a strong candidate for sustainable food systems.	4/5
8. Nankya et al., 2017	Uganda	Household Surveys	NA	Common bean, banana (staples)	Varietal mixtures increased perceived yield by 5.2% (beans) and 28.6% (bananas) over three years.	3/5

9. Tumuhe et al., 2020	Uganda	Participatory Observational	NA	NUCs (e.g., African eggplant, bitter berries, staples (e.g., banana, cassava, millet, beans)	NUCs resilient to harsh conditions, nutrient-rich, address hidden hunger. use natural pest control/preservation, supporting sustainability; cultural value preserves heritage; proposes conservation	3/5
10. Omotayo et al. (2025)	South Africa	Cross-sectional survey (quantitative, MESR model)	None	NUCS (mung bean, Bambara groundnut, monkey orange, cleome, amaranth) vs. staples (maize, sunflower, potato)	Households adopting UCs had 21–26% higher WPI (improved water availability) and lower HFIAS (better food security) than those relying on staples. UCs require less water, are more climate-resilient, and promote dietary diversity, stabilizing food access and reducing seasonal hunger. The study highlights the urgent need to integrate UCs into mainstream food systems and policy for sustainable, resilient agriculture under climate stress.	5/5
11. Msweli et al. (2024)	South Africa (arid/semi-arid)	Systematic review (PRISMA, narrative synthesis, thematic/comparative analysis)	None: uses WUE, economic benefits as proxies	NUCS: sorghum, cowpea vs. Staples: Maize, wheat	NUCs reduced water use by 30–40%, Sorghum and cowpeas are highly drought-tolerant (+25% survival rate), maintaining >70% yield during droughts and soil health, outperforming water-intensive staple crops like maize and wheat. These NUCs exhibit superior water use efficiency through deep roots and stomatal control, thriving in water-scarce conditions. Require 40% fewer inputs, reducing environmental impact compared to staple crops.	5/5
12. Makeo et al., 2024	Uganda	Ethnobotanical Survey and Proximate Analysis	NA	NUC: Dioscorea hispida (yam)	94% use it for treating ailments (e.g., diabetes, malaria, cancer), supporting health and sustainability. Nutritional composition: 72.3% moisture, 11.67% carbohydrates, 6.1% fiber, 5.65% protein, 1.2% fat, 3.05% ash, diversifying diets. Sold for 2,500–4,000 UGX (0.66–1.06 USD), indicating economic viability. Low input needs and flood resilience	4/5

13. Chimwaza et al., 2024	Uganda, South Africa	Scoping Review	none	33 NUCs (e.g., millets, legumes, roots, tubers, indigenous vegetables, fruits) vs. staple crops (maize, rice, wheat)	NUCs are adapted to marginal environments, require fewer inputs, and are resilient to drought and climate variability. They enhance food and nutrition security, dietary diversity, and agro-biodiversity, and serve as “fail-safe” crops during staple crop failure. NUCs support smallholder livelihoods, empower women, and can reduce reliance on high-input staples.	
14. Pasipanodya et al., 2025	South Africa	Participatory Rural Appraisal (Survey, Focus Groups, Interviews)	NA	NUC: Bambara groundnut (<i>Vigna subterranea</i>) Staples: Maize	Bambara groundnut is drought-tolerant, thriving in low-rainfall (240–651 mm) and sandy soils, unlike staples like maize. - High nutritional value (20–40% protein, 53% starch, 10.3% fiber) complements cereal diets, addressing malnutrition. - 61% of farmers perceive soil fertility benefits via nitrogen fixation, reducing input needs compared to staples. - Grown on small plots (<1–2.5 ha) with minimal inputs, enhancing resilience.	4/5
15. Munialo et al., 2024	South Africa	Systematic Review (PRISMA)	NA	NUCs: Finger millet, pearl millet, yam, sweet potato, amaranth, nightshade, Marama bean, soybean, cashew nuts Staples: Maize, rice, wheat, cassava, potato	- Maize dominates research (58% funding), while NUCs like finger millet, yam, and amaranth have low outputs. - Nutrient gains from NUCs: finger millet (P, K, Fe, fiber), amaranth (Ca, Mg, carotene), yam (K, fiber), enhancing nutrition security. - NUCs are climate-resilient, low-input, and biodiversity-friendly, unlike staples like maize. - Reorienting research to NUCs could increase nutrient diversity and food security.	4/5

16. Ndiovu et al., 2024	SSA	Systematic Review (PRISMA)	NA	NUCs: Bambara groundnut, finger millet, yam, cowpea, amaranth, sorghum Staples: Maize, wheat	- NUCs are resilient to drought, heat, and salinity, unlike climate-sensitive staples like maize. - High nutritional value (e.g., protein, fiber in Bambara groundnut) addresses micronutrient deficiencies, enhancing dietary diversity. - NUCs require fewer inputs, support biodiversity, and improve soil fertility, unlike staple monocultures. - NUCS thrive on marginal and degraded land thus avoids deforestation	4/5
17. Veldsman et al., 2023	South Africa	Nutrient Analysis	NA	NUC: Bambara groundnut (<i>Vigna subterranea</i>) Staple: Maize (mentioned for comparison)	- BGN is drought-tolerant, with low water use, ideal for SSA's climate challenges. - High protein (8.54 g/100 g EP), lysine (0.655 g/100 g EP), and fiber (11.4 g/100 g EP), complementing maize's low lysine (70:30 ratio increases DIAAS from 0 to 20.7%). - Nitrogen fixation enhances soil fertility, unlike maize monocultures.	4/5
18. Ali & Bhattacharjee (2023)	SSA	Systematic Review	NA	NUC: Finger millet, foxtail millet, pearl millet, buckwheat, amaranth Staples: Rice, wheat, maize, barley, sorghum	- NUCs are nutritionally superior (e.g., finger millet >10x calcium vs. rice, quinoa 14% protein, supporting dietary diversity and food security. - NUCs are climate-resilient, thriving in drought, salinity, and nutrient-poor soils with lower water and input needs - NUCS reduce GHG emissions by 20-40% due to lower input dependency - NUCS produce 2-3x more calories on poor soils	4/5
19. Nhamo et al., 2022	South Africa	GIS Suitability Mapping	NA	NUC: Bambara groundnut (<i>Vigna subterranea</i>) Staple: Maize (mentioned for comparison)	- BGN is drought-tolerant, with low water and input needs, unlike water-intensive maize. - Rich in proteins, fiber, and micronutrients, addressing malnutrition versus maize-heavy diets. - Nitrogen fixation and degraded land suitability enhance sustainability.	3/5

20. Leakey et al., 2022	SSA	Systematic Review	NA	NUCs: Baobab (<i>Adansonia digitata</i>), marula And several others. Staples: Maize, others (mentioned for comparison)	- NUCs (e.g., baobab, marula) are drought-tolerant, nutrient-rich, and biodiversity-friendly, unlike vulnerable staples like maize. - Enhance nutrition (e.g., baobab's vitamin C, marula's oil) and livelihoods via agroforestry. - Participatory domestication and commercialization (e.g., baobab pulp, marula beer) boost incomes.	4/5
21. Dunjana et al., 2022	South Africa	Narrative Review	NA	NUC: Sorghum (<i>Sorghum bicolor</i>)	- Sorghum's drought tolerance and low water needs outperform maize in semi-arid South Africa. - Provides nutritional diversity, supporting food security. - Low input requirements enhance environmental sustainability.	3/5
22. Popoola et al., 2022	SSA	Narrative Review	NA	NUCs: Orphan legumes Staples: Maize, rice, wheat	- Orphan legumes are drought-tolerant, nutrient-rich (19.4–22.5 g/100 g protein), and nitrogen-fixing, outperforming maize in marginal environments. - Enhance nutrition, soil fertility, and livelihoods	4/5
23. Mudau et al., 2022	South Africa	Systematic Review	NA	NUCs: moringa, carob, cancer bush, wild ginger, bitter gourd, kale, taro, cactus pear, etc. vs. staple crops (maize, wheat, etc.)	NUCs are nutrient-dense, have significant medicinal and nutraceutical value, and are adapted to marginal environments with low inputs. They support food and nutrition security, health, and rural livelihoods, and can enhance resilience and sustainability of food systems. Their cultivation can diversify diets, reduce environmental impact, and empower vulnerable groups.	4.5/5
24. Mugiyo et al. (2021)	South Africa	GIS-based MCDA-AHP spatial suitability analysis	NA	Sorghum, cowpea, amaranth, taro (NUCs)	High suitability for NUCs in marginal/drought-prone areas; supports food system resilience and diversification	4/5

25. Mandizvo et al., 2021	South Africa	Systematic Review	NA	NUC: Citron watermelon (<i>Citrullus lanatus</i> var. <i>citroides</i>)	- Citron watermelon's drought tolerance (e.g., citrulline accumulation, deep roots) and low input needs outperform maize in dry environments. - Rich in proteins, vitamins, and antioxidants, enhancing nutrition.	4/5
26. Musokwa & Mafongoya, 2021	South Africa	Experimental Study	NA	NUC: Pigeonpea (<i>Cajanus cajan</i>) Staple: Maize (<i>Zea mays</i>)	- Pigeonpea's drought tolerance and deep roots enhance resilience compared to maize. - Intercropping yields higher biomass (5513 kg ha ⁻¹) and WUE (9.4 kg mm ⁻¹) than sole crops. - Nitrogen fixation (up to 235 kg N ha ⁻¹) improves soil fertility.	4/5
27. Mabapa et al. (2020)	South Africa	Field experiment; yield and economic assessment	NA	Cowpea (5 varieties, NUC); Maize (staple)	Intercropping increased combined yields (LER > 1), improved gross margins, and enhanced resilience and resource use efficiency Negative: Some cowpea varieties had reduced yield when intercropped;	5/5
28. Rapholo et al. (2020)	South Africa	Field experiment (2 sites, 2 seasons)	Yield (kg/ha), water use efficiency, resource use efficiency	NUC: lablab Staple: Maize	Intercropping with delayed lablab planting maintained maize yields and improved water use efficiency; lablab yields were stable under climate variability; supports sustainable intensification for smallholders. Negative: Lablab yield was low; simultaneous planting reduced maize yield;	4/5
29. Udeh et al., 2020	SSA	Narrative Review	NA	NUC: Bambara groundnut (<i>Vigna subterranea</i>) Staples: Maize,	BGN's drought tolerance and nitrogen fixation enhance resilience compared to maize. - Rich in proteins (18–21%), micronutrients, and	3/5

				rice, wheat (mentioned for comparison)	antioxidants, addressing malnutrition. - Antimicrobial properties reduce pathogen losses.	
30. Mabhaudhi et al., 2019	South Africa	Systematic Review	NA	General NUCS and Staples	NUCs are nutrient-dense, climate-resilient, require fewer inputs, and can enhance agro-biodiversity, dietary diversity, and sustainability. They empower smallholder and women farmers and can reduce malnutrition and environmental impact.	5/5
31. Venter et al., 2019	South Africa	Case Study/Review	NA	Cactus pear (Opuntia ficus-indica, O. robusta) vs. staple crops	Cactus pear is highly drought-tolerant, thrives in marginal soils, and requires minimal inputs compared to staples. It supports food security, nutrition, and income generation, especially for smallholders.	4.5/5
32. Mabhaudhi et al., 2017	South Africa	Systematic Review	NA	NUCs including cereals, legumes, leafy vegetables, indigenous fruit trees	NUCs are drought tolerant, adapted to low water use, and suitable for marginal/semi-arid areas. NUCs are nutrient dense, improve dietary diversity, and support food security and sovereignty, and promote agro-biodiversity and sustainable systems.	5/5
33. Mabhaudhi et al., 2016	South Africa	Narrative Review	NA	NUCs: Bambara groundnut, Cowpea, Sorghum, Pearl millet and yam	- NUCs' drought tolerance and low inputs enhance resilience in marginal South Africa and Uganda environments. - Nutrient-dense, improving dietary diversity and nutrition. - Nitrogen fixation supports soil fertility -Sorghum reduces GHG emissions by 20–40% due to minimal chemical use.	4/5
34. Chivenge et al., 2015	SSA	Review	NA	NUCs: Amaranth, bambara groundnut, cowpea, pearl millet, taro, wild watermelon,	NUCs are drought-tolerant, require fewer inputs, and thrive in marginal environments. They enhance agro-biodiversity, nutrition security, and climate resilience. NUCs support smallholder livelihoods, empower women, and act as "fail-safe" crops during staple crop failures.	4.5/5

				indigenous fruits vs. staple crops (maize, wheat, rice)	NUCS Maintain yield under drought Whereas staples have 30-50% yield decline in droughts	
35. Denison & Wotshela (2012)	South Africa	literature review, interviews, field visits	NA	Lucerne, maize, sorghum, millets, pumpkins, melons, beans	Identifies 15 WHC practices enhancing water use efficiency and agricultural sustainability. In-field rainwater harvesting reduces crop failure risk by up to 8x	3/5
36. Backeberg, G.R. & Sanewe, A.J., 2010	South Africa	Literature Review	NA	NUCS: (amaranth, bambara groundnut, cowpea, African leafy vegetables)	Indigenous crops are well-adapted to local environments, require fewer inputs (especially water and agro chemicals), and can be cultivated without expensive irrigation	4/5
37. Tsubo et al. (2005)	South Africa	Simulation study	NA	Maize (staple), beans (NUC)	intercropping yields LER > 1 (1.1–1.58), indicating higher land productivity than sole cropping. Intercrop EV matches sole maize, and MV matches sole beans (5:1 price ratio), showing economic benefits of beans. Intercropping reduces production risk, enhancing resilience in semi-arid conditions.	4/5
38. Mugisha & Diiro, 2010	Uganda	Cross-sectional survey	NA	Improved maize varieties	Improved maize varieties yield 2,941.5 kg/ha vs. 1,694.5 kg/ha for local varieties but with reliance on external inputs (seeds, extension) limits sustainability	2/5

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